PROCEEDINGS OF THE 43rd FORUM ON THE GEOLOGY OF INDUSTRIAL MINERALS

Edited by James A. Cappa

Forum Sponsored by the Colorado Geological Survey

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FOREWORD

The 43rd Forum on the Geology of Industrial Minerals was held in Boulder, Colorado at the Millennium Harvest Hotel from May 20th to May 25th, 2007. The Forum was hosted by the Colorado Geological Survey and assisted by numerous volunteers from private industry, other state agencies, and the U.S. Geological Survey and Bureau of Indian Affairs. This report presents the technical papers and abstracts of the posters that were given at the technical meeting from May 21st to May 23rd.

The theme of the forum was "Then and Now" and papers were recruited that, in some way, reflected the changes in the industrial minerals industry from the 15th Forum on The Geology of Industrial Minerals, which was hosted by the Colorado Geological Survey in 1979. The 34 technical papers reflected the change in the industrial minerals business and science over the intervening 28 years. An interesting note is that the papers presented at the 15th Forum were mostly from the Rocky Mountain region. The papers from the 43rd Forum were drawn from a wider geographical area, including Zambia, Ukraine, Guyana, and Suriname. The 13 posters again reflected the wide interests of industrial minerals including such exciting ideas as in "Earth Materials in Medicine".

The five field trips visited cement plants, aggregate and dimension stone quarries, clay deposits, analytical laboratories, and a gypsum quarry and wallboard plant.

Colorado State Geologist and Director of the Colorado Geological Survey, Vince Matthews, provided substantial support for the Mineral and Energy Resources Section to spend, what turned out to be, a considerable amount of time organizing and presenting the Forum. Members of the Colorado Geological Survey Staff on the organizing committee who deserve special thanks are Beth Widmann, Jim Burnell, and Chris Carroll. Fund raising is an important part of every Forum and Dave Abbott of Behre Dolbear did a wonderful job of raising enough money to keep the registration cost below $300. Dave Holmes and Lynne Chastain-Carpenter of the Bureau of Indian Affairs worked on the technical sessions and poster sessions respectively. Adrian Charters of Aggregate Industries helped organize field trips. Jim Guilinger and John Keller (consultant Geologist) of World Industrial Minerals produced an outstanding Meeting Handbook. Bill Langer (Mr. Aggregate!!) of the U.S. Geological Survey recruited papers and organized the technical sessions. Tom Newman of Holcim organized the field trips and his wife, Patti Newman, organized the guest field trips- a very important part of every Forum. Thanks to the Newman Family. Jim Reed of Rockware provided computer support, a wonderful sense of humor, and helped his fiancée, Dyan Stratman, with the Silent Auction, which netted over $2,000 to the Bates Scholarship Fund. Paul Schaur of the Colorado Rock Products Association managed the Forum web site. Bill York-Fiern of the Colorado Division of Mining, Reclamation, and Safety organized the exibitors space.

Thank you to all the participants, guests, sponsors, and exhibitors for making the 43rd Forum an interesting and entertaining Forum.

James A. Cappa
Chairman, Organizing Committee of the 43rd Forum

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The 43rd Forum on the Geology of Industrial Minerals expresses our gratitude for the generous support of the following organizations as sponsors and exhibitors. The financial contributions of sponsors and exhibitors play a critical role in making the Forum possible. ***Thank you!***

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The planning committee for the 43rd Forum on the Geology of Industrial Minerals would also like to thank the following individuals and organizations for their support and contributions:

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Annual Meetings of the Forum on the Geology of Industrial Minerals

1st	1965	Columbus, Ohio
2nd	1966	Bloomington, Indiana
3rd	1967	Lawrence, Kansas
4th	1968	Austin, Texas
5th	1969	Harrisburg, Pennsylvania
6th	1970	Ann Arbor, Michigan
7th	1971	Tampa, Florida
8th	1972	Iowa City, Iowa
9th	1973	Paducah, Kentucky
10th	1974	Columbus, Ohio

11th	1975	Kalispell, Montana
12th	1976	Atlanta, Georgia
13th	1977	Norman, Oklahoma
14th	1978	Albany, New York
15th	1979	Golden, Colorado
16th	1980	St. Louis, Missouri
17th	1981	Albuquerque, New Mexico
18th	1982	Bloomington, Indiana
19th	1983	Toronto, Ontario, Canada
20th	1984	Baltimore, Maryland

21st	1985	Tucson, Arizona
22nd	1986	Little Rock, Arkansas
23rd	1987	North Aurora, Illinois
24th	1988	Greenville, South Carolina
25th	1989	Portland, Oregon
26th	1990	Charlottesville, Virginia
27th	1991	Banff, Alberta, Canada
28th	1992	Martinsburg, West Virginia
29th	1993	Long Beach, California
30th	1994	Fredericton, New Brunswick/Halifax, Nova Scotia, Canada

31st	1995	El Paso, Texas
32nd	1996	Laramie, Wyoming
33rd	1997	Quebec City, Quebec, Canada
34th	1998	Norman, Oklahoma
35th	1999	Salt Lake City, Utah
36th	2000	Bath, England
37th	2001	Victoria, British Columbia, Canada
38th	2002	St. Louis, Missouri
39th	2003	Reno/Sparks, Nevada
40th	2004	Bloomington, Indiana

41st	2005	Istanbul, Turkey
42nd	2006	Asheville, North Carolina
43rd	2007	Boulder, Colorado

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Session 1

Geology of IMs in Colorado and other Western States

Industrial Minerals, a Staple in the Economy of New Mexico

By Peter Harben[1], George Austin[2], Gretchen Hoffman[2], Virginia McLemore[2], Margaret Caledon[2], and James Barker[2]

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ABSTRACT

Production of industrial minerals has been and remains important to the rural economy of New Mexico. Industrial minerals constitute about two-thirds of the almost $600 million generated by non-fuel mineral production in New Mexico. In 2005, some 235 mines were registered in New Mexico. This total includes about 40 mineral operations and about 184 active and 11 standby aggregate operations. New Mexico leads domestic production of potash, perlite, zeolite, and travertine. It is 2nd in humate, 4th in pumice, 13th in gypsum, and 11th in salt. Other production includes common and fire clay, scoria, limestone, fly ash, cement, magnetite, silica, and decorative stone. Statistics for industrial minerals produced in New Mexico from 1950 to 2005 are included.

Intrepid Mining and Mosaic each operate potash mines near Carlsbad in Eddy County. World Minerals and Dicaperl operate large perlite mines in Rio Arriba and Socorro counties. St. Cloud Mining operates the Stone House zeolite (clinoptilolite) mine in Sierra County. Travertine is quarried and fabricated west of Belen in Valencia County by NM Travertine.

Humate from weathered coal is produced from five mines in McKinley and Sandoval counties. Pumice is produced in the Jemez Mountains region near Sante Fe in Rio Arriba, Sandoval and Sante Fe counties. Centex operates the White Mesa gypsum mine near Cuba in Sandoval County to feed wallboard plants in Albuquerque and Bernalillo. Salt is produced from brine wells and salt pans near Carlsbad in Eddy County.

Grupos Cementos de Chihuahua produces 500,000 short tons per year of cement at the Tijeras plant east of Albuquerque. Scoria is produced in Dona Ana, Santa Fe, Rio Arriba and Union counties. Fly ash is produced in the Four Corners area at mine-mouth coal-fired power generating plants.

Several industrial minerals show potential for production in the state. At least one company is exploring for garnet. Development of the low-grade nepheline syenite at Wind Mountain in the Cornudas Mountains (Otero County) is on hold. Cretaceous black sandstone in the San Juan Basin has drawn interest for titanium, iron, rare-earth elements, and zircon. Exploration for beryllium in the San Mateo Mountains, Iron Mountain, and Victorio district is on-going.

INTRODUCTION

New Mexico, nicknamed the Land of Enchantment, is the 5th largest state at 121, 355 square miles. Population is small at 1.9 million with 6 percent growth 2000-2005. It is concentrated along the Rio Grande in Albuquerque (494,000), Las Cruces (83,000), Sante Fe (71,000) the state capital, and Rio Rancho (67,000). Climate is semi-arid with an average elevation of about 5,700 feet.

Production of industrial minerals (table 1, 2) has been and remains important to the rural economy of New Mexico. Industrial minerals constitute about two-thirds of the almost $600 million generated by non-fuel mineral production in New Mexico (fig. 1). In 2005, some 235 mines were registered in New Mexico. This total includes about 40 mineral operations and about 184 active and 11 standby aggregate operations. New Mexico leads domestic production of potash, perlite, zeolite, and travertine. It is 2nd in humate, 4th in pumice, 13th in gypsum, and 11th in salt. Other production includes common and fire clay, scoria, limestone, fly ash, cement, magnetite, silica, and decorative stone.

Table 1. New Mexico Summary of Commodity Production, Production Value, Employment, Payroll, Revenue and Ranking, 2005. Source: New Mexico Mining and Minerals Division, 2007.

Mineral	**Production**[1]	**Production Rank**[2]	**Production Value $**	**Employment**[3]	**Reclamation Employment**[4]	**Payroll $**[5]	**Revenue Generated $**[6]	
							State	**Federal**
Coal	29,650,833	11	664,416,940	1,504	111	102,421,067	25,094,186	4,823,263
Copper	290,607,027	3	473,215,363	1,678	80	53,282,124	2,861,402	-
Gold	9,764	10	4,342,969	0	0	-	241,828	-
Iron	-	-	-	2	0	-	-	-
Industrial Minerals[7]	2,466,281	-	200,871,063	600	12	24,365,057	910,418	-
Aggregates[8]	20,014,987	25	128,730,636	1,161	113	20,986,675	1,863,724	-
Magnetite	29,246	-	352,198	0	0	-	-	-
Molybdenum	4,069,790	6	103,267,579	275	16	10,820,427	-	-
Potash[9]	988,782	1	282,710,833	926	0	57,580,288	2,388,008	2,284,837
Silver	203,672	10	1,484,867	1	0	-	6,658	-
Uranium[10]	-	-	-	71	67	1,332,000 $	240,000	-
TOTAL			$1,859,392,448	6,218	399	$270,787,638	$33,606,224	$7,108,100

[1] Production for coal, industrial minerals, aggregates, magnetite and potash is reported in short-tons; copper and molybdenum in pounds; gold and silver in troy ounces.

[2] Production rank is based on 2005 production value in relation to other U.S. states. Sources: Metals, potash, industrial minerals and aggregates, USGS Mineral Resources Program (http://minerals.er.usgs.gov/); Coal, Department of Energy's Energy Information Administration (www.eia.doe.gov).

[3] Category includes direct and contract employees.
Gold, silver and magnetite are co-products of copper production. Employment and payroll for these commodities are reported in the cooper numbers. [4] Reclamation employment is included in total employment numbers. [5] Payroll is for direct employment and does not include contract employees. [6] State revenue includes royalties and rentals from

state trust land mineral leases and severance, resources excise and energy conservation tax revenues.
Federal revenue (fiscal year 2005) includes 50 percent state share of federal royalties.
Sources: State data from New Mexico Taxation and Revenue Department (http://www.state.nm.us/tax/) and the State Land Office (http://www.nmstatelands.org/).
Federal data from Minerals Management Service (http://www.mms.gov/).

[7] Category includes gypsum, perlite, salt, limestone, calcite, dimension stone, silica flux, clay, humate, scoria, pumice, mica and zeolites.

[8] Category includes base course, caliche, clay and shale, crushed rock, dimension flagstone, fill dirt, gravel, limestone, red dog, rip-rap, sand, scoria, topsoil and travertine.

[9] Production is K20 mill production.

[10] Employment and payroll numbers are for permitting, care and maintenance and reclamation activities.

Source: New Mexico Energy, Minerals and Natural Resources Department, Mining and Minerals Division, unless otherwise noted.

Table 2. Production quantity and amount of industrial minerals 1999–2005 from New Mexico Mining and Minerals Division, annual reports.

Mineral	**2005** Production	**2005** Value $	**2004** Production	**2004** Value $	**2003** Production	**2003** Value $
IM [1]	2,466,281	200,871, 063	2,379,183	168,557,974	2,274,999	153,198,856
Magnetite	29,246	352,198	38,141	455,345	-	-
Potash[2]	988,782	282,710,833	1,069,265	237,819,345	1,064,485	202,166,863
Aggregates	20,014,987	128,730,636	34,547,659	103,810,297	14,838,772	77,848,579

Mineral	**2002** Production	**2002** Value $	**2001** Production	**2001** Value $	**2000** Production	**2000** Value $
IM[1]	2,393,754	174,603,868	2,561,004	166,705,643	2,925,926	162,402,617
Magnetite	-	-	-	-	-	-
Potash[2]	1,014,529	189,611,426		191,732,005	1,377,801	215,737,596
Aggregate	15,441,510	73,499,682	12,353,090	61,115,960	13,752,251	66,810,485

Mineral	**1999** Production	**1999** Value $	**1998** Production	**1998** Value $	**1997** Production	**1997** Value $
IM[1]	3,703,430	176,750,513	3,299,061	148,974,895	2,445,951	72,522,308
Magnetite	-	-	-	-	-	-
Potash[2]	1,342,026	235,202,181	1,330,341	231,079,006	1,639,995	179,916,805
Aggregate	13,404,230	60,677,102	12,285,797	50,182,561	12,504,844	107,851,657

[1] includes gypsum, perlite, salt, limestone, calcite, dimension stone, silica or silica flux, clay, humate, scoria, pumice, mica and zeolites

[2] includes caliche, clay and shale, crushed rock, flagstone, gravel, limestone, red dog, sand, scoria, topsoil/dirt, travertine

[3] production is K_2O mill production

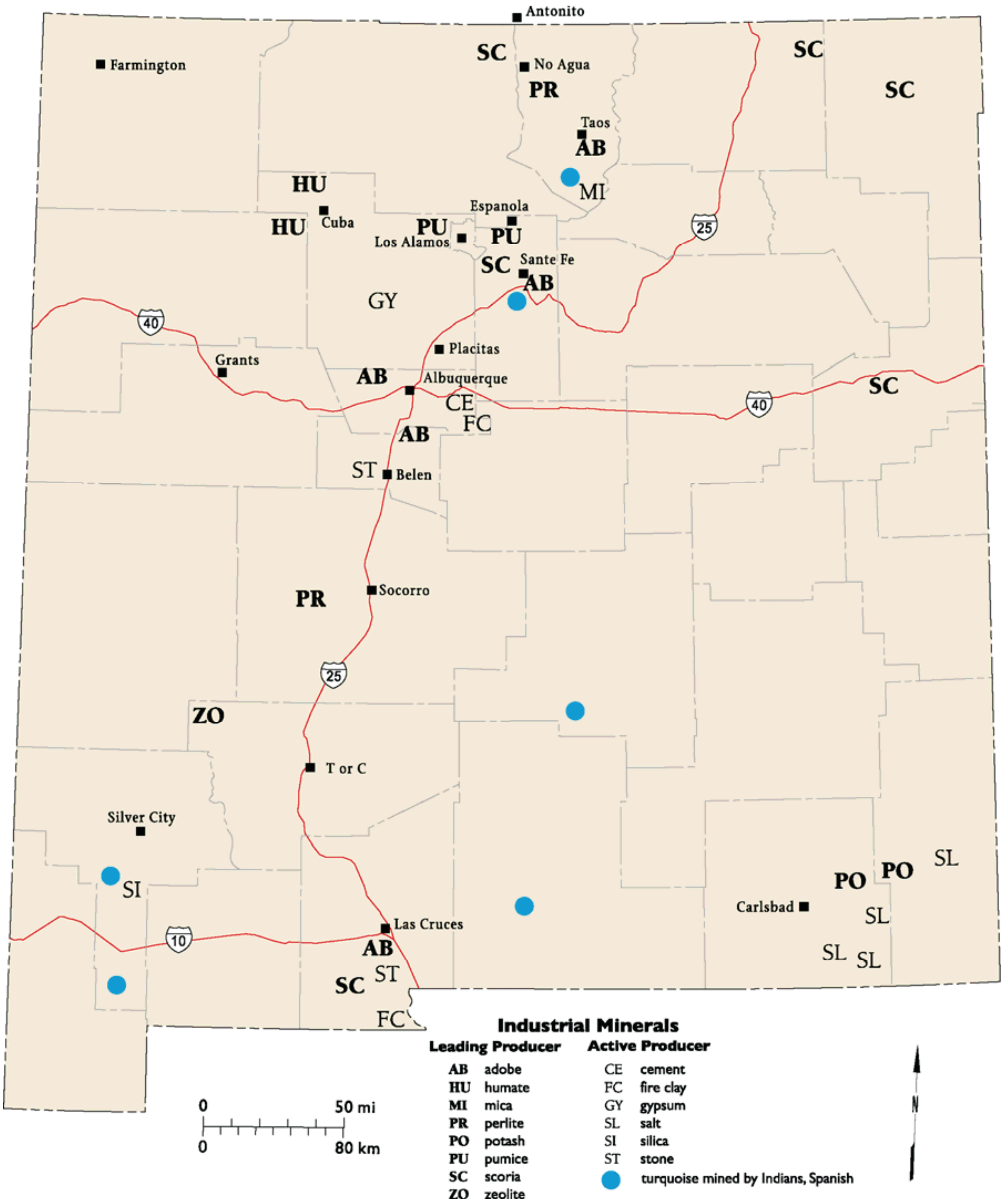

Figure 1. Location of industrial minerals produced in New Mexico. Common industrial minerals not shown are crushed stone (primarily in the east and west thirds of the state), caliche (southeast), coal clinker (northwest), sand and gravel (Rio Grande valley), limestone (south of Interstate 40) and decorative stone (north of Interstate 40).

Claim Staking

The Bureau of Land Management (BLM) coordinates mining claims on federal land with the state of New Mexico and the U.S. Forest Service. The claim staking process is set by the state and claims are recorded at both the County Seat and the BLM. The BLM administers and adjudicates activity on the several types of claims—most are for locatable minerals on lode or placer claims. Federal lands are often divided in ownership between surface estate and mineral estate. In recent years the trend has been to include the surface owner more directly in claim staking. This has made the two estates co-equal. The BLM will not accept claims that do not include an agreement with the surface owner. When the two parties cannot agree legal action may be required.

Currently, Congress has imposed a moratorium on mineral patent applications, and the BLM is not accepting any new patent applications at this time. Five patent applications in New Mexico were "grandfathered" under the moratorium and are being processed.

New Mexico Rank in Frasier Institute Study

The New Mexico Mining and Minerals Division (2007) analyzed the recent biannual study by the Fraser Institute, a free market research group in Canada, as follows. "[The study] offers some evidence about how the mining industry views the attractiveness of New Mexico compared to other jurisdictions. Mining executives were surveyed concerning both the policy climate and the mineral potential of various jurisdictions around the world, and their responses were used to create several indices. On a scale of 0 to 100, New Mexico received a 53 for policy potential and a 36 for mineral potential. Compared to other states, New Mexico finished sixth highest overall out of fourteen. States such as Colorado, Montana and Wyoming scored lower than New Mexico. Perhaps more significantly, nine of the top ten jurisdictions were foreign, while eight of the bottom ten were U.S. states."

ADOBE (Austin)

Mud is one of the oldest building materials used by man. Spanish conquest of the New World spread the use of wooden molds to produce a standard adobe brick. Today, the word "adobe" is used to describe various earth building materials and techniques, usually referring to sun-dried adobe brick now used in the U.S., but is also applied to puddled adobe structures, mud-plastered logs or branches (Jacal or waddle-and-daub), pressed-earth blocks, and rammed-earth walls or pisé (Austin and Holmes, 2006; Ferm, 1985).

Mud construction has been, and is, used in many countries in many parts of the world. In the U.S., the Southwest from Texas to California is perhaps the part of the country most commonly associated with this type of construction. Of the states in this area, New Mexico has the dominant reputation for adobe use. Indeed, in New Mexico the "Santa Fe" style has made adobe, not only acceptable, but chic.

Raw Materials

Adobe soil used by present-day New Mexican adobe producers, and probably past adobe producers as well, is principally from stream deposits, particularly Holocene (Recent) terrace deposits and older, loosely compacted geologic formations, such as the Santa Fe Group (Tertiary) located in the Rio Grande valley. Most producers use a sandy loam (50 percent clay and silt) associated with or derived from the Santa Fe Group. Some producers use a mixture of materials from the screened fines of aggregate operations in the river valleys combined with varying amounts of sand to produce the proper mix.

Mineralogy

X-ray diffraction analyses of whole-rock samples show the major constituents of New Mexican adobe soils are quartz and feldspar, with lesser amounts (in order of abundance) of calcite, clay minerals, and gypsum. The quartz, feldspar, most of the clay minerals, and some calcite are derived from the mechanical/chemical breakdown of older rocks units. Some clay minerals, much of the calcite, and all the gypsum is precipitated from evaporating water.

Although smallest in percentage of size fractions in earth construction material from New Mexico, clay-size particles are the most compositionally variable in commercial adobe soils. However, the clay mineral groups in this size fraction consist of about equal parts of expandable clay minerals (smectite and mixed-layer illite/smectite [I/S]), non-expandable clay minerals (kaolinite, illite, and chlorite), with minor quartz, calcite, and feldspar (Austin, 1990; Smith and Austin, 1996). The smectite is universally calcium-rich and the I/S is disorganized, randomly interstratified smectite and illite.

Expandable clay minerals tend to be more “sticky” than nonexpandable varieties and thus are more effective in binding silt and sand particles together. Expandable clay minerals also form colloidal suspensions with water and therefore moisture, whether as rainfall or ground water, has the greatest effect on adobe soils with the largest proportion of smectite and I/S.

For past and present adobe producers in New Mexico, expandable clay minerals were sometimes a problem. Cracking of drying adobe brick is due most probably to the somewhat large proportion of smectite and I/S in adobe soil; soils with higher clay content but lower smectite and I/S content, will have less tendency to crack. Cracking is extreme on windy days when the shrinking clay structure is changing rapidly. Drying slowly over many calm days allows multiple layers of finely crystalline calcite (and some gypsum) to form on a clay-size scale strengthening the bricks and preventing cracks. The resulting adobe wall can resist torrential late-summer rains for long periods if the adobe bricks do not contain too much clay material and is properly cured.

Chemical properties

Soils in the arid New Mexican climate are typically alkaline. Ground water near the Rio Grande valley is generally hard to extremely hard, containing total dissolved solids (TDS) ranging from about hundred to several thousand parts per million (Anderholm, 1987). Soluble salts, notably calcium carbonate and calcium sulfate, precipitate as this water evaporates.

Adobe walls in New Mexico are remarkable durable in this climate. With proper care, walls hundreds of years old are durable. Great care is taken to keep the wall interiors dry. Walls in the Native American pueblos are recovered with a “natural plaster” or a yearly basis as part of “community service” by the inhabitants. The natural plaster has about the same mineral and chemical composition as the walls themselves but is a slightly finer grained. It is expected to wash off slowly during the year and to be replaced during the next replastering. The slow weathering of the plaster apparently is due to calcite and gypsum precipitation from the mixing water that forms a caliche-like bond between grains as the mud slowly dries.

Leaching tests with EDTA (ethylenedinitrilotetraacetic acid) on 25 commercial New Mexican adobe soils suggest that commercial soils contain an average of about 90 percent insoluble and 10 percent soluble material; the latter is dominantly calcite and some gypsum (Austin, 1990). In that study, the soluble material ranged from 36 weight percent to essentially zero. Adobe soils with the smallest amount of soluble material were also the highest in sand and larger-size particles.

Physical properties

The common statement by New Mexican adobe producers is that their soil mix is usually one-half sand and one-half “clay” or “fines” (silt and clay), but commercial adobe soils range from 85 to 99 weight percent nonclay-size particles (Smith and Austin, 1996). The average grain-size composition was 67 weight percent sand-and-larger, 27 weight percent silt, and six weight percent clay. The wide variation of particle sizes, particularly in the sand-and-larger-size and silt-size grains, affects the penetration of paint or stabilizer sprayed or painted on walls. Adobe walls with high clay- and/or silt-size content would need the largest amount of preservative. An abundance of clay-size particles in adobe soils causes excessive cracks as blocks dry in an adobe yard. To combat this, producers add straw and/or additional sand to the mud mixture.

Large-scale commercial adobe producers use adobe soils with less clay-size material than do small-scale commercial and non-commercial adobe producers. Some of the former are as low as about one weight percent clay, whereas many of the latter are between 8 and 15 weight percent (Smith and Austin, 1996). In part, this is because large-scale commercial adobe producers use stabilizers that not only protect blocks from rain damage but aid in consolidation of the drying soil mix as well.

Other properties

Traditionally, materials are evaluated for thermal properties based on measurements known as R- and U-values. The R-value is an indicator of the ability of a wall to insulate effectively. Adobe walls have very low R-value because they commonly consist of 10 inch or 14 inch blocks covered with a thin stucco on the outside and thin gypsum plaster on the inside. What is not considered, and is of critical importance in the wall of masonry-mass walls such as adobe, is the heat storage capacity of the wall, which determines the length of time that passes before a steady state of heat flow is achieved. The higher the heat storage capacity of the wall, the longer period of time it will take for heat flow to reach a steady state. In real situations, external temperatures, in particular, are changing constantly, so that a true steady-state condition is rarely achieved. Because diurnal changes in the arid Southwest are typical 30 to 50°F, the “fly-wheel effect” thus will keep adobe buildings daytime temperatures cool in the summer and warm in the winter.

Thick massive walls of a typical adobe are well-known sound deadener making these homes remarkably quiet. Windows in older adobe building are normal small further adding to the quietness. Newer solar adobe homes take advantage of the many sunny days in arid climates with large windows but use well-insulated glass to retain much or the sound deadening characteristics of adobe dwellings.

The identification of radon gas as a health hazard in homes and the low-strength materials used in adobe homes when they are in seismically-active areas have caused owners to wonder about the safety of their adobe structures. Radon enters buildings through cracks, particularly when they are closed and have a negative air pressure as is commonly true during the heating months in winter, and accumulates in low spots. Although adobe buildings have not been shown to have significantly more radon than other types of construction, good ventilation and positive interior air pressure are the easiest ways to prevent a buildup of the radon (Smith and Austin, 1996).

Seismic activity is very destructive in many parts of the world that use low-strength masonry walls. Adobe buildings in the U.S. are commonly constructed with one- and two-stories, and on concrete slab foundations. Designing the slab to resist cracking both during normal life of the structure and possible earthquakes is prudent in seismic areas. Recent work in California suggests that a combination of proper slab construction, reinforcing walls with rebar, the use of wire mesh used both inside and outside the building beneath the plaster and stucco, interconnected bond beams and roof beams at the top of walls, and buttresses can all serve to reduce hazards relating to earthquakes (Tibbets, 1986).

Other physical properties that make adobe construction appealing are that homes so constructed are water resistant, flame retardant, unaffected by termites, and energy efficient. In addition to the preservation of nighttime cool temperatures in the summer and daytime heat in the winter, the energy efficiency is due to the sun-dried method of production, rather than using high heat to produce masonry brick or cement. Wright (1978) stated that it takes over 300 times more commercial energy to produce a concrete block equal in volume than a sun-dried adobe block.

Technology

Several varieties and sizes of earthen brick are produced throughout the American Southwest; these include traditional adobe, semi stabilized and stabilized adobe, New Mexican terrónes (cut-sod brick), quemados (burnt adobe), and machine-pressed-earth block; in addition, rammed-earth walls are constructed without brick (McHenry, 1984; Smith and Austin, 1996). The two major types of adobe brick currently produced in New Mexico are the traditional adobe brick and the semi-stabilized adobe brick.

Traditional (untreated) adobe bricks

Often called untreated or sun-dried adobe brick, traditional adobe is made with soil composed of sand with some larger particles, and of silt and clay. Straw is sometimes added for strength and to prevent excessive cracking during drying. The moistened soil mixture commonly is packed into a brick-like mold, released, and allowed to dry and “cure” for several weeks before use.

Stabilized adobe bricks

Fully stabilized adobe brick is defined by the New Mexico Building Code as water-resistant adobe made of soil with certain admixtures that limit the brick's seven-day water absorption to less than four weight percent. A fully stabilized adobe brick usually is made with 6 to 12 weight percent of asphalt emulsion (California Research Corporation, 1963; Scheuch and Busch, 1988). Exterior walls constructed with stabilized mud mortar and brick require no additional protection and can be left exposed without stucco. The production of fully stabilized adobe brick is very low because most walls are stuccoed with water-resistant plaster, and the additional waterproofing agent adds extra cost.

Semi-stabilized adobe bricks

Semi-stabilized adobe brick was developed by major adobe producers in New Mexico and is classified as a water-resistant brick because of the addition of three to five weight percent of a stabilizer or water-proofing agent (California Research Corporation, 1963; Scheuch and Busch, 1988). The stabilizer protects the brick from rainstorm damage during the curing process. Asphalt emulsion is the primary stabilizer because of the ease of use and the low cost, but 5 to 10 weight percent Portland cement produces the same result. Semi-stabilized adobe is made the same way as traditional adobe, except mixing the stabilizer into the adobe soil prior to packing it into a form (fig. 2).

Figure 2. Front-end loader charging the hopper of an automatic adobe lay-down machine at the Adobe Factory, Alcalde, N.M. Once the hopper moves across the 25-space mold filling it, the lay-down machine picks up the mold and moves it to the next position leaving the adobes to dry.

Pressed-earth blocks

Pressed-earth blocks presently make up a small portion of earth brick used in New Mexico (Smith and Austin, 1996). The CINVA-Ram hand-operated press was developed by a Chilean engineer in the 1950s and has been used in New Mexico, but most pressed-earth blocks in the state are made by gasoline- or diesel-powered machines. Several have been designed and used in the past in New Mexico to press the adobe soil mixture into a form, minimizing the amount of time required between forming the block and placing it into the wall. Portland cement or asphalt emulsion has been used to partly or fully stabilize pressed-earth blocks. Most producers are small-volume and/or part-time, or non-commercial.

Rammed-earth walls

Rammed-earth homes commonly have much thicker walls than most other earthen dwellings, up to 36 inches thick. Wooden or metal concrete-type forms are put in place on stone or concrete footings and 15- to 20-cm-thick layers of moistened soil are put between the walls of the forms. Hand or hydraulic tampers are used to pound the soil into the shape of the form, compacting and reducing the volume of the mixture by 25 to 30 percent (McHenry, 1984; Middleton, 1987). Once the layers of tamped soil reach the desired height, the forms are removed and the wall is allowed to dry. Portland cement is the common stabilizer used.

Producers say rammed-earth walls continue to harden, or cure, during the first year after construction. New Mexico’s two rammed earth producers commonly produce between three and five rammed-earth homes each year.

Distribution

The American Southwest has long had a love affair with adobe and the landscapes of New Mexico, Arizona, Texas, and California contain many examples of enduring adobe homes. Old military forts, churches, and commercial buildings also attest to its popularity. New Mexico, both historically and today, is the largest domestic producer and user of adobes. Three to four million adobe bricks and pressed-earth blocks have been produced in New Mexico each year by 15 to 20 commercial manufacturers (Smith and Austin, 1996).

Today, most builders purchase the adobe bricks from commercial yards located throughout New Mexico. The adobe-block operation is a labor-intensive but fuel-efficient seasonal industry with the production of blocks usually limited by the number of frost-free days. The principal standard-size adobe brick produced and used in New Mexico measures 4 x 10 x 14 inches and weigh approximately 30 pounds (Smith and Austin, 1996).

Economic Factors

Tradition is the most important factor in determining markets for adobe materials. In areas that have a strong tradition of mud construction, adobe is appealing, even preferred. In other areas where the population is not familiar with adobe, or worse, considers it beneath them to live in such buildings, new adobe buildings will not be built and old one will disappear. An example of the former area is Santa Fe, New Mexico. The “Santa Fe style” of construction is adobe pueblo and territorial style (Smith and Austin, 1996). Adobe buildings are preferred by many wealthy landowners, and even contractors who use other types of construction mimic the adobe styles.

Adobe may be made on the construction site, but in recent years it is more likely to be made in adobe yards and transported to building sites on flat-bed trucks. Although transport to distant construction sites in uncommon, some producers ship adobes several hundred miles. The problem is not normally in the availability of the raw material. Acceptable, if not superior, adobe can be made with most native raw materials, providing a qualified adobe maker is involved. The reason is the land owner wants an adobe home and contractors in the immediate area have neither the training nor talent for this type of construction.

Rammed-earth construction methods require than the walls be made at the building site. Consequently, the normal method of construction is to use local materials or materials that have not been transported far.

AGGREGATE (Austin)

Aggregate is defined as: (a) a mass or body of rock particles, mineral grains, or a mixture of both; (b) any of several hard, inert materials, such as sand, gravel, slag, or crushed stone, used for mixing with a cementing or bituminous material to form concrete, mortar, or plaster; or used alone, as in railroad ballast or graded fill (Jackson, 1997).

In New Mexico, sand and gravel from the Rio Grande valley supply for the state's need for aggregate. Crushed stone is produced principally along the eastern and western border areas and to supply specialized needs.

Sand and Gravel

In 2006, construction sand and gravel valued at $7.9 billion was produced by an estimated 3,800 companies from about 6,000 operations in 50 states. It is estimated that about 49 percent of the 1.28 billion tons of construction sand and gravel produced in 2006 was for unspecified uses. Of the remaining total, about 45 percent was used as concrete aggregates; 22 percent for road base and coverings and road stabilization; 14 percent as construction fill; 12 percent as asphaltic concrete aggregates and other bituminous mixtures; two percent for plaster and gunite sands; one percent for concrete products, such as blocks, bricks, and pipes; and the remaining four percent for filtration, railroad ballast, roofing granules, snow and ice control, and other miscellaneous uses (Bolen, 2007).

Recent reports of the U.S. Geological Survey and New Mexico Bureau of Mines/Geology and Mineral Resources show that nearly every county in New Mexico has produced sand and gravel at one time or another. However, the major activity is concentrated near the major centers of population and industrial expansion. Albuquerque in Bernalillo County in central New Mexico has consistently led the state for many years. This city was followed by Las Cruces in Doña Ana County in the south central part of the state, Roswell in Chaves County in the east central part of New Mexico, Farmington in San Juan County in the northwest, Raton in Colfax County in northeast, and Carlsbad and Artesia in Eddy County in the southeast.

Sand and gravel deposits of New Mexico are so widespread and abundant that much of the accompanying map would be covered if all geologic units that contain potential sources of sand and gravel were shown. Therefore, only the largest, most continuous deposits are included to demonstrate their distribution. Principal deposits consist of alluvial sand and gravel of Pleistocene to Recent age that comprise the bed of the Rio Grande and adjacent terraces and plains. They extend from north of Bernalillo in Sandoval County southward to the Texas and Mexico borders. Such deposits are particularly widespread in Doña Ana, Luna, and Sierra Counties in south-central New Mexico. Similar large deposits are found on the Rio Grande in Taos County to the north and on the drainage of the Pecos River in Chaves, Eddy, and Lea Counties to the southeast. Smaller deposits of the same type and pocket-like lenses filling old channels, known as bolson deposits, are found in the upper reaches of the Pecos River, along the Canadian River, and their tributaries in the northeastern part of the State.

Some of sand and gravel deposits are undoubtedly derived from sandstones and conglomerates of the Ogallala Formation which crops out mainly along the eastern boundary of the state and of the Santa Fe Group in the north-central part. Similar deposits are also associated with older Tertiary (Paleocene, Eocene, and Oligocene) and Cretaceous formations that include the Wasatch, Torrejon, and Puerco Formations and the Ojo Alamo Sandstone in the western part and the Raton and Galisteo Formations in the eastern part of the state. One of the largest areas of these formations appear to be of primary importance mainly in San Juan County and especially near Farmington and Aztec in the northwestern part of the state.

Crushed Stone

In 2006, the crushed stone industry was valued at $13.1 billion and their products was produced by 1,200 companies operating 3,200 quarries, 85 underground mines, and 190 sale/distribution yards in all 50 states. Of the total crushed stone produced in 2006, about 70 percent was limestone and dolomite; 16 percent, granite; 8 percent, traprock; and the remaining 6 percent was shared, in descending order of tonnage, by sandstone and quartzite, miscellaneous stone, marble, volcanic cinder and scoria, calcareous marl, shell, and slate. It is estimated that of the 1.69 billion tons of crushed stone consumed in 2006, 32 percent was for unspecified uses, and 18 percent was estimated for non-respondents to U.S. Geological Survey canvasses. Of the remaining 850 million tons reported by use, 85 percent was used as construction aggregates, mostly for highway and road construction and maintenance; 13 percent for chemical and metallurgical uses, including cement and lime manufacture; one percent for agricultural uses; and two percent for special and miscellaneous uses and products (Willett, 2007).

Crushed and broken stone are obtained from a variety of igneous and sedimentary rocks in New Mexico, but the largest volume is produced from limestone. Desirable qualities for use as crushed and broken stone include strength, durability, and ease of quarrying and processing. The rock should crush to firm, roughly equidimensional granules, with minimum amounts of dust and powder. Bonding quality is important in rock to be used as aggregate. Limestone ordinarily makes ideal concrete aggregate, and basalt, and limestone generally adhere to bitumen better than granite or sandstone, although any of these rocks may serve as aggregate. Rock which is to be used as railroad ballast, should be hard, durable, and crush to sharp-edged particles. Stone to be used for decorative purposes is selected chiefly on the basis of attractive appearance, but strength and durability are also important.

Where sand and gravel is not available, particularly on the eastern plains, caliche is the only source of larger size material is crushed for use as in the base course in highway construction. Many counties maintain there own pits supplying base course. Along the relatively heavily populated Rio Grande valley, sand and gravel pits are the principal source of aggregate. A few quarries for special needs exist in this area, as the quarries supplying the cement east of Albuquerque and the cinder pits producing scoria in Doña Ana County in south central New Mexico. Scoria also comes from cinder pits west of Santa Fe and in Union County in northeast New Mexico. Railroad ballast from a Precambian quartzite is produced in Torrance County at the Pedernal quarry of Western Rock Products. Large-diameter crushed rock is produced from an andesite at the Vado quarry in Doña Ana County south of Las Cruces for use in rock walls. Limestone is quarried at the Tinaja pit in the Zuni Uplift of Cibola County in west central New Mexico for use in concrete. Crushed limestone is produced at the Chino Limestone quarry for use in copper production.

CEMENT (McLemore)

Cement commonly refers to hydraulic cement, especially Portland cement. Hydraulic cements are those that have the property of hardening under water and are the chief binding agents for concrete and masonry. Portland cement was patented by Joseph Aspdin of Leeds, England, in 1824, and today, it is the predominant variety of hydraulic cement. The name "Portland" was chosen because the set cement resembled a building stone quarried from the Isle of Portland off the southern coast of England. Most of the cement produced in the U.S. is Portland cement; masonry cement is used for stucco and mortar.

Portland cement concrete is a principal construction material. New Mexico produces seven different types of cement at a total estimated capacity of 500,000 short tons/year of cement from the Tijeras cement plant operated by Grupos Cementos de Chihuahua (GCC) near Albuquerque to markets in New Mexico and southern Colorado. The cement shortage of 2005 is mostly over, but the price of cement remains at 2005 prices, $130 per cubic yard, as compared to 2004 when cement was $45 per cubic yard (Trenkle, October 2006). The Tijeras cement plant was commissioned in 1959 and GCC took over operations in 1994. The main ingredient in cement is limestone (Madera Limestone) mined at Tijeras with additional varying quantities of iron, sandstone/shale, alumina, and gypsum (locally obtained from throughout New Mexico). There is no cement production in El Paso, but Cementos de Chihuahua has two plants in the Juarez area supplying cement to the El Paso market. The older Juarez plant is capable of producing about 500,000 metric tons annually. The newer Samalayuca plant is rated at 1.2 million metric tons. Cementos de Chihuahua also is the parent company of Rio Grande Portland Cement. Southdown, Inc. operates a cement plant at Odessa, Texas, about 250 mi east of El Paso, which has a rating of approximately 750,000 metric tons. These four cement plants produce almost all the cement needed in the New Mexico-west Texas area.

CLAY (Austin)

The term clay is somewhat ambiguous unless specifically defined, because it is used in three ways: as a diverse group of fine-grained minerals, as a rock term, and as a particle size term. As it is used here, it is a fine-grained, natural, earthy, argillaceous material; the particle size of clays is very fine and is generally considered to be about 2 µm or less; and the minerals are hydrous silicates composed mainly of silica, alumina, and water. Several of these minerals also contain appreciable quantities of magnesium, iron, alkalis, and alkaline earths. Many definitions state that a clay is plastic when wet. Most clay materials do have this property, but not all (Harvey and Murray, 2006).

In 2006, clay and shale production was reported in 42 states. About 220 companies operated approximately 800 clay pits or quarries. In 2006, domestic producers estimated that sales or use will be 41.3 million metric tons valued at $1.62 billion, excluding palygorskite-type fuller’s earth. Major uses for specific clays were estimated to be as follows: for ball clay, 40 percent floor and wall tile, 31 percent sanitaryware, and 29 percent other uses; for bentonite, 26 percent absorbents 23 percent foundry sand bond, 22 percent drilling mud, 13 percent iron ore pelletizing, and 16 percent other uses; for common clay, 61 percent brick, 16 percent lightweight aggregate, 15 percent cement, and 8 percent other uses; for fire clay, 46 percent refractories and 54 percent heavy clay products; for fuller’s earth, 86 percent absorbent uses and 14 percent other uses; and for kaolin, 61 percent paper and 39 percent other uses (Virta, 2007).

Clay materials have been used for building construction in New Mexico for many centuries, for Indians were making crudely shaped adobe blocks prior to the arrival of the first Spanish settlers. Adobe was the most common building material for many years and is still used in new construction, particularly in north-central part of the state. The extensive use of sun-dried adobe prevented the expansion of New Mexico's brick and tile industry at the same rate as in other states. Also, none of the very valuable clays that can be sold at distant markets have been mined on a large scale in the state.

The clay materials now produced commercially or consumed locally are miscellaneous clays used in the manufacture of brick and portland cement; loam and soil used for adobe; fire clay used in low- and moderate-heat-duty refractory products; and pottery clay. Minor quantities of miscellaneous clays are occasionally produced for use in drilling mud. Bentonite has been produced in the State, but the only bentonite plant operating in 2007 is near Belen in central part of the state and it processes Ca-bentonite mined in Arizona. Virtually all the "meerschaum" mined in the U.S. came from two districts in Grant County prior to World War I, and there has been no recent production.

The suitability of clays in New Mexico for various uses depends on physical properties that are controlled by the mineral and chemical composition of the clay. The common clay minerals in New Mexico include kaolinite, calcium montmorillonite, illite, halloysite, sepiolite, chlorite, and mixed-layer clay minerals. All clays contain nonclay mineral impurities. Quartz, cristobalite, tridymite, feldspar, titanium minerals, carbonate minerals, and mica are common in many clays and gypsum and organic matter are abundant in others. The value of clays for most uses varies directly with the purity of the clay mineral present; however, for some products nonclay minerals or organic matter having certain properties are important. Physical properties of clays, one or more of which make them suitable for different uses, include plasticity, bonding strength, color, vitrification range, deformation with drying and firing, resistance to high temperatures, gelation, wall-building properties, viscosity of slurries, swelling capacity, ion-exchange capacity, and absorbent properties (Patterson and Holmes, 1965).

Bentonite

Bentonite is a clay material that has altered from volcanic ash or tuff and it is ordinarily composed chiefly of montmorillonite. One kind of bentonite known as Wyoming or sodium type has very high-swelling capacity, extremely fine particle size, and other properties that make it valuable for use in well-drilling mud; as a bonding material for foundry sands and in pelletizing fine-grained iron ores, where high dry strengths are required; and as a relatively impervious lining for reservoirs, irrigation ditches, and stock tanks. A second kind of bentonite called calcium bentonite, southern type, or non-swelling is mineralogically similar to the Wyoming type but has different physical properties. Non-swelling bentonites are ordinarily not as efficient in drilling muds as the Wyoming type but they are more suitable for bonding materials requiring high-green strength, for catalysts in refining petroleum, bleaching clays, for cat litter, as a desiccant, and other purposes. The United Desiccants plant near Belen uses Ca-bentonite from Arizona to produce desiccant clays.

A deposit with properties similar to the Arizona clay has been identified in New Mexico, but the bed, while fairly widespread is only about 0.5 m thick and is located on the Santa Ana Pueblo land (Austin, 1994). Bentonite occurs in most counties in New Mexico, but has been mined only on a small scale at a few localities and none are mined at present.

Kaolin and Refractory Clays

Kaolin and refractory clays are a group of clays having related mineralogy and chemical composition. These clays are classified according to uses, as: (1) kaolin or china clays, (2) ball clays, (3) halloysites, and (4) fire clays. Large quantities of fire clay and kaolin and smaller quantities of halloysite and ball clay are used in making refractory products. Both ball clay and kaolin are used in making tableware, whiteware, and other ceramic products. Both halloysite and kaolin are used as catalysts in refining petroleum. Kaolins are used in adhesives, medicines, cosmetics, fillers, chemicals, and many other purposes and because of their content of Al_2O_3, 39.50 percent in theoretically pure form, kaolins are commonly considered as a possible source of alumina. Clays that may be classified as kaolin, halloysite, and fire clay occur in New Mexico, but ball clay has not been discovered in the state. No halloysite deposit has been exploited (Patterson and Holmes, 1965).

The kaolin and refractory clays in New Mexico occur under various geologic conditions and have been used principally as fire clay and as mixtures with common clay and shale in making brick and tile. No deposits have been exploited recently; however, some operations have tried to start in the 20th century. Deposits, part of which are composed of chiefly kaolin and part montmorillonite and nonclay mineral impurities, have altered from volcanic rock along Copperas Creek in northern Grant County in southwestern New Mexico. These deposits were briefly mined to supply brick plant at Silver City with a raw material for making light-colored face brick.

Large deposits consisting of a mixture of highly crystalline kaolinite and cristobalite occur in hydrothermally altered tuffs and other volcanic rocks along the continental divide about 14 miles west of Winston, Sierra County. Parts of this deposit consist of rather uniform light-colored clay, but much of it contains appreciable vein quartz or other forms of silica and only partially altered volcanic rock. A few metric tons of clay from this deposit were used experimentally in making ceramic tile, and were explored in some detail and evaluations for use as paper coater are being made by private interests: however, the presence of considerable amounts of cristobalite and tridymite make this deposits unsuitable for this use (Isik and others, 1994).

Kaolin clay occurs in sedimentary beds at the top of the Morrison Formation of Jurassic age and in the basal part of the overlying Dakota Sandstone of Cretaceous age at many places in northwestern New Mexico. The best exposures of this clay are on Mesa Corral and Mesa del Camino, near the highest part of north-facing Mesa Alta, Rio Arriba County. At this locality bedded kaolin on an old erosion surface at the top of the Morrison Formation has been partly reworked and both kaolin clay chips and kaolin cement are present in the overlying Dakota Sandstone. A sample of this clay tested is superduty refractory clay, and a sample of the sandstone cemented with kaolin from the overlying Dakota Sandstone is a high-duty refractory material (Patterson and Holmes, 1965).

Fire clays, commonly associated with coal beds, occur in sedimentary formations of Cretaceous age in several counties. The largest production of these clays has been in the Gallup region, McKinley County, where thick beds of plastic, moderately thick beds of semiplastic, and thin seams of flint clay occur in the Mesaverde Group. These deposits were worked as early as 1898. The highest production was in 1907 when 27,000 metric tons of fire-clay mortar, raw fire clay, and fire brick were shipped (Patterson and Holmes, 1965). Clay production in the Gallup coal field has been negligible in recent years, because the best grade clays are not thick and can only be mined by underground methods.

Small-scale production of fire clay from strata of Cretaceous and Paleocene age has been reported at a number of localities, and a few undeveloped deposits occur at scattered localities. Clays and shales in the Dakota Sandstone have been used for refractories at Ancho, Lincoln County (Van Sant, unpublished report; Austin, 1993), and at Las Vegas, San Miguel County (Van Sant, unpublished report). Shales and clays in the Vermejo and Raton Formations were used many years ago in making coke ovens at Dawson, Colfax County, and are, therefore, probably at least low-grade refractory clays. Some of the clay in the Mesaverde Group mined for brick in the Carthage coal field, Socorro County (Talmage and Wootton, 1937), may have been suitable for low-heat-duty fire brick (Van Sant, unpublished report).

Miscellaneous Clays and Shales

Common clays and shales used in making brick and tile and for other purposes have been mined at a number of places in New Mexico. Plants using these materials have operated at various times since 1900 at most centers of population, including Albuquerque, Santa Fe, Gallup, Aztec, Farmington, Flora Vista, Fruitland, Ship Rock, La Luz, Las Vegas, Socorro, San Antonio, Silver City, and others (Talmage and Wootton, 1937). Most of the plants supplied local markets and closed after such demands were satisfied. The only brick plants in operation in the spring of 2007 are those of the Kinney Brick Co. in Albuquerque and the American Eagle Brick Company in New Mexico just west of El Paso, Texas. The pit of the Kinney Brick plant is in the Pine Shadow Member of the Wild Cow Formation, Madera Group of Upper Pennsylvanian age. The American Eagle Brick pit consists of marine shales and siltstone of Lower Cretaceous age. Miscellaneous clays of Pennsylvanian age are used in making portland cement at Tijeras, east of Albuquerque.

Clays and shales for miscellaneous uses have been mined from several types of rocks, including altered volcanic rock and sedimentary formations ranging from shale of Devonian age to flood-plain alluvium of Recent age. The Devonian Percha Shale west of Silver City was mined to mix with clays from Copperas Creek to obtain colored brick. Clays and shales have been mined recently east of Mesquite, Doña Ana County, to supply brick plants in El Paso, Texas; and they were formerly mined northeast of Santa Fe to supply the State Penitentiary plant. Clays and shales in the Mancos Shale and Mesaverde Group of Cretaceous age were mined for brick at a number of places in northwestern New Mexico, including the former plant at Gallup; similar materials mined in the old Carthage coal field were used in the plant at Socorro; and clays and shale of Cretaceous age have been used for brick on a small scale in northeastern New Mexico. Red gypsiferous highly plastic clays of probable Tertiary age were dug near Monument, Lea County, and used for drilling mud in the Hobbs oil field, and small tonnages of organic shales in the Blanco pit, Chaves County, are also used in drilling mud. Alluvial clays of Recent age were formerly used for low-quality brick at Albuquerque and Socorro (Patterson and Holmes, 1965).

Pottery Clay

Plastic clays have been used on a small scale in making pottery, chiefly Indian wares and art pottery objects. One material used was a dark shale interbedded with limestone of Pennsylvanian age (Talmage and Wootton, 1937). This shale becomes plastic when ground and pugged, and fires nearly white. It was formerly used in making art pottery of Mexican design at the La Luz pottery works, Otero County.

Plastic clays suitable for Indian wares are dug locally near Gamerco, McKinley County, and near Española, Rio Arriba County. A deposit of plastic pottery clay, which probably is kaolin altered from volcanic rock, in secs. 2 and 11, T. 23 N., R. 2 E., northwest of Santa Fe, formerly supply local ceramic needs (Patterson and Holmes, 1965).

Meerschaum

Meerschaum (sepiolite), $Mg_8(Si_{12}O_{30})\ (OH)_4\ (OH_2)_4 \bullet NH_2O$, is a tough clay material so lightweight that dry meerschaum (German word for sea foam) will float on water. Meerschaum can be carved and shaped and has been used for nearly 200 years in making pipes and other articles for smokers, and small quantities have been used for a number of other purposes, including an absorbent for nitroglycerine.

"Meerschaum" was discovered along Sapillo Creek, Grant County, New Mexico, in 1875. An estimated 2 million pounds of meerschaum had been shipped before World War I from the meerschaum mining district, on Sapillo Creek approximately 34 miles north of Silver City, and from the Juniper district, along Bear Creek 12 miles northwest of Silver City. Production of meerschaum ceased shortly before World War I, and the only recent meerschaum operation, other than by mineral collectors, was in 1943, when approximately 1,000 pounds was shipped for experimental purposes in an attempt to find improved materials for insulators in radios (Patterson and Holmes, 1965). However, recent X-ray diffraction analysis indicates that the "meerschaum" consists of palygorskite, $Mg_5\ (Si_8O_{20})\ (OH)_2\ (OH_2)_4 \bullet 4H_2O$, rather than sepiolite.

FLY ASH (HOFFMAN)

Pozzolans by definition are siliceous or siliceous and aluminous materials that in themselves possess little or no cementitous value but will, in a finely divided form and in the presence of moisture, chemically react with calcium hydroxide in cement at ordinary temperatures to form compounds possessing cementitious properties. Fly ash from coal combustion has pozzolanic properties that make it saleable as a mineral additive to concrete.

During the coal combustion process to produce electricity, the non-combustible material in coal becomes molten and either remains in the combustion chamber as slag, drops to the bottom of the combustion chamber as bottom ash, and the lighter particulate matter is carried out of the chamber in the flue gasses, as fly ash. This molten material moves upward with the flue gas, cooling rapidly with the air movement giving 60 percent of the particles a spherical shape. Electrostatic precipitators (ESPs) or mechanical precipitators such as bag houses or cyclones, capture the fly ash from the flue gas. ESPs have a 99+ percent efficiency in capturing fly ash and are the most common anti-pollution devise used by generating stations. The ratio of bottom to fly ash is dependent on the burner and boiler types with fly ash percentage varying from 65 percent-85 percent. Fly ash consists mainly of SiO_2, Al_2O_3 and Fe_2O_3. The chemical makeup of the fly ash is dependent on the type of coal and the amount of unburned carbon (loss on ignition) remaining in the fly ash is dependent on the combustion process. The type of flue gas desulfurization method can affect the characteristics of the fly ash. Placement of a dry scrubber system in line before the fly ash is captured coats the fly ash with the desulfurization byproducts ($CaO + CaSO_4$) and cannot be used as a pozzolan.

Three major coal-fired generating stations in New Mexico sell a portion of the produced fly ash to Salt Rivers Minerals Group (SRMG) formerly Phoenix Cement in Scottsdale, Arizona. The characteristics that make fly ash saleable are its pozzolanic properties that can offset the amount of cement required for concrete. Other characteristics fly ash imparts to concrete are increased durability, lower heat of hydration, ease of pour, lower permeability, and strength and durability over time. Fly ash from all three generating stations is Class F fly ash, indicating a minimum of 70 percent SiO_2+Al_2O_3+Fe_2O_3 composition (American Society for Testing Materials, 2003).

Not all the fly ash captured meets the specifications as a pozzolan. Size is an important factor and the coarser material (>44µm) is not suitable as a pozzolanic material. To meet ASTM C618 (American Society for Testing Materials, 2003) specifications, no more than 34 percent or the fly ash can be retained on a 45µm (325-mesh) sieve. To ensure the consistency of the fly ash SRMG has classifiers at the Four Corners and San Juan generating stations that control the size characteristics of their product. They also do continual testing of the fly ash coming from the different generating units to ensure consistency in the percent LOI (loss on ignition), fineness, and color of the fly ash.

Table 3 shows the amount of fly ash sold and disposed in thousands of short tons for all three generating stations. The offsite disposal for both the San Juan and Four Corners generating stations is fly ash returned to the adjacent coal mines, San Juan and Navajo, for use in stabilization and reclamation (Dale Diulus, SMRG, 2007 personal communication). Over half of the fly ash sold from both San Juan and Four Corners is trucked to a rail loadout facility near Gallup, a distance of about 100 miles. The remaining fly ash from these plants near Farmington, New Mexico is trucked to the job site or silos near population centers. SRMG has storage facilities in California, Arizona, New Mexico, and Colorado (Salt River Materials Group, 2006). Escalante fly ash can be shipped by rail, the power plant is along a spur to the main line of Burlington Northern- Santa Fe railroad, or trucked via Interstate 40.

Table 3. Fly Ash produced and sold from New Mexico generating stations for 2005.
Data from DOE-EIA form 767 (Department of Energy, 2005). Reported in thousands of short tons.

Category	Escalante	San Juan	Four Corners	Totals
Total produced	186.8	1054	1548.6	2789.4
Landfill				
Ponds			461.7	461.7
Onsite use/storage	96.2			
Offsite disposal		823	789.3	1612.3
Sold	90.6	231	297.6	619.2
percent sold	48.5	21.9	19.2	22.2

Primary use of New Mexico fly ash is in concrete and road construction. Over 50,000 tons of fly ash from the San Juan generating station was used in construction of State Highway 550 from Bloomfield to Bernallilo, New Mexico completed in November 2001 (Public Service Company of New Mexico, May 2002). The New Mexico Department of Transportation requires 20 percent minimum Class F fly ash when using aggregates that is reactive or potentially reactive to prevent alkali-silica reaction (New Mexico State Highway and Transportation Department, 1999). Alkali-silica reaction is a common problem in the southwest because of the predominance of reactive material in aggregate, such as opal, chalcedony, or siliceous shales. ASR occurs when silicate minerals react with alkali metal ions (Na_2O and K_2O) in Portland cement paste to from gel. With moisture, the gel swells, causing expansion and cracking of the concrete around individual aggregate (Hoffman, 2000).

SRMG also markets the hollow, glassy sphere portion of the fly ash called cenospheres. Cenospheres are lightweight, have a high compressive strength, and high melting point. These glassy spheres have many uses as fillers in paint, plastics, and industrial putty, as well as acoustical insulation.

GYPSUM (McLemore)

Gypsum is a soft mineral (hardness of 1.5–2) with the formula $CaSO_4 \cdot 2H_2O$, and is typically formed in sedimentary environments. Gypsum is used primarily in the manufacture wallboard for homes, offices, and commercial buildings; other uses include the manufacture of Portland cement, plaster-of-Paris, and as a soil conditioner.

Eagle Materials operates the White Mesa mine near Cuba and two wallboard plants (Albuquerque and Bernalillo). The annual gypsum wallboard capacity at the Albuquerque plant is 430 million square feet and at the Bernalillo plant 495 million square feet, The mine has an estimate reserves of more than 48 million tons that should last mare than 50 years (Eagle Materials, 2006) Other smaller gypsum mines are operated in Sandoval and Doña Ana County. The Castile Formation is an extensive occurrence of gypsum in the Delaware Basin of west Texas and southeastern New Mexico.

HUMATE (Hoffman)

Humates, as a lithologic term, include oxidized coals and lignites, organic-rich mudstones and claystones and some sandstone that have concentrations of humic substances, such as the Jackpile Sandstone found in the Grants uranium belt. In New Mexico, oxidized coals and organic rich mudstones and claystones are mined for their humic materials. Humates are often used as a soil additive, although they are also used in drilling mud for increased circulation. They are most beneficial on sandy soils lacking in clay material. The humic and fulvic acids in the humate are organic colloids and act like clays to help retain water and nutrients in the root zone of the soil. Humate lowers the pH of alkaline soil, increasing the plant nutrient availability and stimulating growth of microorganisms (Hoffman and others, 1995)(fig. 3).

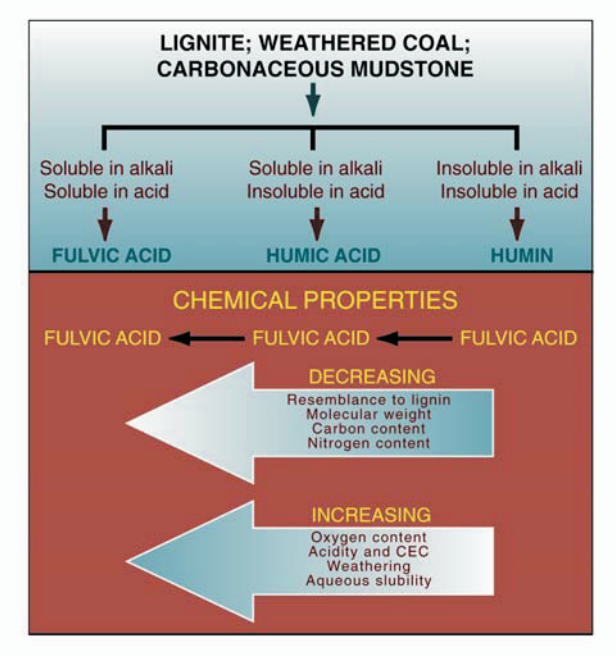

Figure 3. Formation of organic acids from lignin and coal.
Source: Hoffman, G. K., Verploegh, J., and Barker, J. M., 1996.

Humate-bearing rocks are mined using front-end loaders that place the material in stockpiles for processing at the mill. The humate is crushed, screened, and shipped in bulk, or bag in super sacks to commercial users. Some companies run the humate through an extraction process to produce a humic-rich liquid. Most humate is sold to commercial farms and applied to fields at a rate of 448 to 672 kilogram/hectare , depending on the pH of the soil (Shomaker and Hiss, 1974). Bagged humate or a humic liquid is also sold at local nurseries for home gardening. Transporting humate is generally by truck, but rail is used for some shipments.

There are six operators in northwest New Mexico currently producing humate (table 4). Markets for New Mexico humate include all 50 states, plus Central America, the Caribbean and Taiwan (B. Reid, personal communication). Humate production in New Mexico for 2005 was 29,797 short tons and sales of 24,050 short tons. Total value of sales was $2,436,687, averaging $101/short ton (Susan Lucas Kamat, Mining and Minerals Division, Energy, Minerals and Natural Resources, 2007, personal communication).

Table 4. New Mexico Humate Producers. Data from Susan Lucas Kamat, Mining and Minerals Division, Energy, Minerals, and Natural Resources.

Company	Mine Name, Location (County)	Mill, Location (County)
Menefee Mining, Dallas TX	Star Lake, Menefee – McKinley	Menefee – Sandoval
Mesa Verde Resources, Placitas, NM	Pueblo Alto, and Star Lake-McKinley	Mesa Verde – Sandoval
Morningstar Corp., Farmington, NM	Morningstar – McKinley	Morningstar – San Juan
Rammsco, Inc. Katy, TX	Eagle Mesa – Sandoval	
U-Mate International, Inc. Scottsdale, AZ	U-Mate- McKinley	
Horizon Ag-Product, Modesto, CA	San Luis- Sandoval	

MAGNETITE (McLemore)

Iron ore as magnetite is shipped from the magnetite tailings at Phelps Dodge's Cobre mine in Grant County and is used by cement plants to increase the strength of their cement. The Smokey mine in the Capitan Mountains, Lincoln County has produced magnetite-hematite from contact-metasomatic deposits for the cement plant

PERLITE (Barker)

The perlite industry in the U.S. continued to undergo rapid change and increased competition in 2006 as it did in 2005. This affected New Mexico producers in several ways. World Minerals acquired Basin Perlite in Milford, Utah and itself was acquired by IMERYS in 2005. Basin was subsequently permanently closed in 2006. The Dicaperl operation at No Agua, New Mexico was also placed on standby as was the Dicaperl microspheres plant at Antonito, Colorado. Dicaperl produces microspheres at the former Noble plants in Nevada and Oklahoma. Total U.S. production in 2006 was 457,000 metric tons, continuing the decline seen nationally and in New Mexico over the last few years (table 5 and 6). Perlite imports to the eastern and Gulf coasts of the U.S. from Greece by S&B reached 275,000 metric tons in 2006. This market remains well protected by high rail rates from western U.S. perlite plants. Minor amounts of perlite exported to Canada and to the Pacific Rim partially offset imports. Since 2002, domestic apparent consumption has dropped about 12 percent mainly due to lower demand for perlite used in construction-related materials (Bolen, 2007).

Table 5. U.S. perlite production and imports (1000 metric tons).

Parameter	2001	2002	2003	2004	2005	2006^{e}
Production	588	521	493	508	508	457
Imports	175	224	245	238	196	275
Exports	(43)	(42)	(37)	(37)	(32)	(32)
US Consumption	720	703	701	709	672	700

^{e} Estimated Source: Bolen, 2007

Table 6. Estimated 2006 production of processed perlite sold by the three largest producers in the U.S.

Perlite Operation	Production^{e} 1000 st	Production^{c,r} 1000 metric tons	Percent of Total
Harborlite No Agua, NM	185	168	37
Harborlite Superior, AZ	45	41	9
Harborlite Milford, UT	6	5	1
Dicaperl Socorro, NM	152	138	30

Dicaperl No Agua, NM	0	0	0
Cornerstone, Lakeview, OR	100	91	20
Other perlite USA	16	14	3
U.S Total	503	457	100

[e] estimated [c,r] calculated and rounded from estimated

The average price of perlite in the U.S. rose to $42.72 per metric ton in 2006. End use distribution principally for expanded perlite including microspheres was construction 61 percent (down from 62 percent), horticultural aggregate 14 percent, fillers 11 percent, filter aids 7.5 percent (up from 7 percent), and other 6.5 percent (Bolen, 2007). Crude perlite was produced by seven companies operating nine mines in seven western states. The two bright spots for crude perlite sales remain either very coarse grades for horticultural perlite (hort) or very fine grades for perlite microspheres. Filter aids increased slightly. Perlite was expanded at 62 plants in 31 states (Bolen, 2007).

The hort market continues to experience limited supply and high prices. The highly value-added microspheres market continues to grow. Microspheres are functional fillers used mainly in joint-compound for wallboard installation. In addition, microspheres are utilized in numerous other uses including textured coatings, cultured marble and plastics. Product development of microspheres continues to meet consumer demand for ever-lower density. List prices (Santini and Barker, 2006) for microspheres depend upon packaging and whether they are uncoated or coated (with silane or silicone) and range from $0.20–$0.30 per pound or $0.44–0.66 per kg ($400–600 per short ton or $440–660 per metric ton).

Microspheres production for the world in 2006 was by five firms, all in the U.S.: Silbrico, Dicaperl (Grefco), Harborlite (World Minerals; Basin), Therm-O-Rock We and Therm-O-Rock East. Only Harborlite and Dicaperl have a captive source of perlite. Perlite mining is currently active at Socorro (Dicaperl) and No Agua Peaks (Harborlite).

Dicaperl

Dicaperl, a division of Grefco, operated two mines in New Mexico until the El Grande mine at No Agua Peaks was placed on standby in 2006. The Socorro operation currently is one of two operating mines in New Mexico.

Socorro

The Socorro deposit is granular perlite, with no obsidian, in a 7 Ma old, high-potassium, high-silica rhyolite. Mining is by auger scrapers feeding a conveyor belt to the drying and screening plant. The Dicaperl Socorro mine and screening plant is in sec. 27 T. 3 S., R. 1 W. and employs 30 people including manager Tim Hall. The mine is adjacent to the plant and occupies 70 to 90 acres on patented claims. The Socorro mine was one of the first perlite mines in the U.S. when it opened in 1949. It was closed from 1959 to 1975, but a drill-hole intercepted over 600 ft of perlite showing it to have very large reserves. The operation produces about 5-6 railcars per week or about 150,000 short tons/year, mainly in fine grades for microspheres or coarse grades for hort.

About 98 percent of the crude is moved from the Socorro facilities to customers by rail, primarily in 100 short tons bottom-dump railcars. Some is moved in PD railcars needed for pneumatic unloading of finer sizes. About two percent of crude perlite is trucked to customers requiring perlite in 50 lb sacks or 1 m^3 super sacks. Dicaperl expansion plants are in Lafayette, Louisiana, and Jackson, Mississippi, and take about 10-15 percent of the total crude perlite production. Customers for the Socorro perlite are in Alabama, Arizona, California, Colorado, Florida, Georgia, Illinois, Indiana, Iowa, Kentucky, Michigan, New Mexico, Oklahoma, Pennsylvania, Tennessee, Texas, and Wisconsin. About 10 percent of the product is exported to foreign countries, principally Canada, with a small amount to Mexico. About 60 percent of the Socorro Dicaperl output goes for ceiling tile. Most of the remainder is used by the horticulture market and a minor amount goes into filter aids, wallboard, and pipe insulation.

El Grande mine

The El Grande mine at No Agua Peaks was a single flow altered to granular perlite with considerable obsidian in sec. 15, T. 29 N., R. 9 E. on the southwest flank of the four No Agua Peaks. The No Agua Peaks are composed of late Tertiary extrusive rhyolitic rocks dated at 4.2 Ma (Whitson, 1982). Mining was primarily by ripping and scrapping. The mine fed a sizing plant whose output was trucked to Antonito, Colorado, for further shipping (nationwide) or expansion.

The Dicaperl Antonito plant shipped 35–40 railcars per week of processed perlite and ~6,350 metric tons per year of expanded perlite (shipped only by truck) before going on intermittent status in the early 2000s. Total annual production from the operation was about 200,000 metric tons per year. The Antonito plant had three vertical furnaces (one 18 inch and two 28 inch in diameter).

Dicaperl shipped about 20 percent of their crude product to company-owned Chemrock Corp. plants in Florida, Indiana, Maine, and Tennessee. About 80 percent of the product went to outside customers in Florida, Idaho, Illinois, Indiana, Maine, Massachusetts, Missouri, North Carolina, Ohio, Oregon, Pennsylvania, Tennessee, Texas, and Wisconsin. About 50 to 60 railcars of crude perlite were shipped from Antonito each week.

The Antonito facility included two vertical expanders of 18.5 inch and 30 inch diameter. Expanded perlite was bagged and shipped to California, Colorado, Connecticut, Idaho, Kansas, Montana, New Mexico, New York, North Carolina, Oregon, Texas, Washington, Canada (Ontario), and Mexico. The expanded perlite was shipped mainly by truck in 25, 20, and 18-20 lb paper bags (2-ply, Kraft). One railcar of expanded perlite was shipped from Antonito each week.

About 50 percent of Dicaperl perlite was used in acoustical ceiling tile, 32 percent as block fill and other aggregates, 10 percent as horticultural perlite, and about 8 percent as filter aid.

Harborlite

The Harborlite No Agua deposit, a series of flows is more geologically complex than the adjacent Dicaperl single flow to the west. Production comes from the South and West Hills (about 50 percent each) and all of the West Hill production comes from the A pit. Area I northeast of the plant is slowly being developed. Output from the Antonito, Colorado sizing plant is from 50 to 55 railcars of sized crude per week, but only about one PD car per month. Total yearly production is up from about 250,000 short tons. Plants in California, Florida, Illinois, Mississippi, Pennsylvania, Minnesota, Texas, Virginia, and Indiana plants now use Harborlite No Agua perlite. About 49 percent goes into acoustical tile, 49 percent into fesco (roof board), one percent into silica flux for foundries, and one percent into horticulture.

The perlite is both granular and pumiceous, although some denser material similar to classical perlite is at the core of the hills. In general, a lateral progression from denser perlite, to granular to pumiceous exists from South Hill southward. Some fine-grained, gray-to-clear obsidian is present in the "classical" and granular perlite, but the pumiceous perlite contains virtually none. Perlite is ripped 70-80 percent of the time (West Hill is all ripped; South Hill has some blasting), except for the hardest classical perlite. Blasting accounts for 20 to 30 percent, using ANFO.

Sized crude perlite is shipped by company bottom-dump trucks 24 mi from the No Agua screening plant to the rail-loading facilities at Antonito, CO. Perlite is loaded into bottom-dump or PD 100 short tons railcars at the rate of about 30 bottom-dump and 1-2 PD railcars per week. Less than 5 percent of the ore is shipped by truck, mostly to local or small markets or those lacking rail service.

Former Producers and Exploration Targets

Past production of perlite occurred at Brushy Mountain, Grants, and Leitendorf Hills. Exploration for perlite continues in New Mexico and other western states. In New Mexico, exploration targets include Wallace Ranch, McDonald Ranch, and Schwartz in southwestern New Mexico. The entire southwestern portion of New Mexico is a good exploration target.

Former producers

The three former perlite producers in New Mexico are: Silbrico, U.S. Gypsum and Silbrico.

Silbrico. The Brushy Mountain perlite deposit is ~10 miles east-southeast of No Agua Peaks. It consists of a pumiceous perlite that was most recently mined by Silbrico in the early 1980s. It was initially an underground mine that was completed as an open pit. The age, origin, and character of the perlite was similar to those of the No Agua deposits, but the large amount of fine waste at the mine and the long haul to Antonito made the operation unprofitable.

U.S. Gypsum. The U.S. Gypsum (USG) mine was north of Grants in a rhyolitic dome consisting of concentric envelopes of perlite and obsidian (Barker and others, 1989). Potassium-argon dates on the obsidian and perlite indicate that the perlite is 3.3 ± 0.3 Ma old (Bassett and others, 1963). The friable, well-fractured perlite was mined using front-end loaders and was trucked eight miles to a processing plant (recently demolished and the site reclaimed) adjacent to rail in Grants. Production was about one car of crude perlite per week (<10,000 short tons/year) through the 1990s. Output was for captive uses in USG ceiling tile and plaster. Perlite was shipped from the Grants crushing plant primarily to USG plants in Indiana, New York, Ohio, and Texas, where it is expanded and used in Thermofill plaster.

Leitendorf Hills. Massive brownish-red to dark-green perlite/pitchstone crops out at the Leitendorf Hills (Weber, 1965) as irregular lenses and seams of glass (water content ranges from 2 to over 5 weight percent) and alteration products in a rhyolite dome (McLemore and Elston, 2000). The deposit is eight miles south-southwest of Lordsburg. The deposit crops out for ~3.2 km, is up to 0.8 km wide and 150 m thick, and has an estimated volume of ~23 million m^3

(Flege, 1959). Expanded aggregate was produced briefly in the early 1950s but the variable perlite was impractical to mine. Recent expansion tests at the New Mexico Bureau of Geology on samples from the old loading tipple were about 25 lbs/ft^3. Three quarries in the southern part of the Lordsburg district produced 5,000 metric tons of expanded aggregate in 1952–1954. The stony rhyolite gangue and variability in the deposits made them uneconomic (Flege, 1959).

Selected exploration targets

The Wallace Ranch deposit (Scharkan, 1992) is about 15 miles southwest of Riverside at Pine Canyon and just west of Bald Knoll in sec. 19, T. 16 S., R. 18 W. via NM-180 and 16 miles of dirt road. It is a gray, banded, granular perlite breccia, 15 to 60 ft thick, under black classical perlite, from 6 to 10 ft thick. Water content of the perlite is from 1.73 to 2.00 weight percent and expanded density ranges from 2.4 to 11.9 lbs/ft^3. The resource appears to be large but the long haul to rail, partly unpaved, makes development difficult (Austin and Barker, 1998).

The McDonald Ranch perlite deposits crop out along Burro Cienega ~20 miles south of Silver City in T. 22 S., R.15 W. and T. 22 S., R. 14 W. (Scharkan, 1992). Weber (1965) reports that the main body has a tabular form up to 30 m thick. Water content in the perlite is 1.73 to 5.78 weight percent. Expanded density is 2.5 to 3.5 lbs/ft^3. Development began in the late 1970s and early 1980s and picked up again in the late 1990s. Excessive variability in the quality of the classical perlite and the long truck haul to the Southern Pacific railroad at Gage, New Mexico make development difficult. The outcrop extends ~1.5 km along strike. It is black glass, with clear feldspar or altered white phenocrysts, and is ~2−75 m thick including lenses (Austin and Barker, 1998).

The Schwartz perlite deposit (Scharkan, 1992) is east of Schwartz and 15 miles north of City of Rocks State Park. It is southwest of Tom Brown Canyon about 1.1 miles west of NM-61 in sec. 34, T. 18 S., R. 10 W. and sec. 3, T. 19 S., R.10 W. The perlite outcrop extends about one mile along strike and consists of black glass with clear feldspar or altered white phenocrysts and varies from 6 to 250 ft thick including lenses. Water content is about 3 to 4 weight percent and expanded density ranges from 5.95 to 11.03 lbs/ft^3. The total resource is unclear and the variability of the perlite makes development difficult (Austin and Barker, 1998).

POTASH (Harben)

Potassium is the third most widely used fertilizer nutrient after nitrogen and phosphorus and this use accounts for more than 90 percent of total potash consumption supplied as potassium-bearing minerals, ores, and processed products. The most common form is potash, potassium chloride or KCl, or more correctly muriate of potash (MOP), with a minimum analysis of 60 percent K_2O and differentiated by grain size as granular, coarse, standard, and soluble. Most fertilizer-grade MOP is colored pink to red due to iron oxide and clay content and contains 60–60.5 percent K_2O with 2.0–3.0 percent NaCl and other impurities; refined grades (62.0 percent K_2O and higher with a maximum of 1.0 percent NaCl) are white and are used primarily for industrial applications plus soluble fertilizer solutions and suspensions. The mineral langbeinite, a double sulfate of magnesium and potassium, $K_2SO_4 \bullet 2MgSO_4$, a.k.a. sulfate of potash magnesia (SOPM) or KMS, is used as a specialty fertilizer and an animal feed additive. Theoretically, this natural source of SOPM contains 22 percent K_2O and 18 percent MgO and is produced commercially in New Mexico and Ukraine (Harben, 2002; Prud'homme and Krukowski, 2006).

The potash industry is regarded as an oligopoly with just 14 countries producing a product essential for all agriculture and more than three quarters of world output produced by Canada, Russia, Belarus, and Germany (Harben, 2002). In the U.S., a relatively modest producer with 4 percent of the world output and a net import reliance of 80 percent, New Mexico is the leading producer. Commercial production of almost 1 million tons of K_2O valued at some $280 million (Kostick, 2007) is centered on the Carlsbad mining district of Eddy and Lea counties in the southeastern part of the state where the Salado Formation in the Permian Delaware Basin contains sylvite, langbeinite, and lesser quantities of various sulfate minerals in a dozen potash horizons spread over an area of about 5,000 km^2 (Barker and Austin, 1999). Based on sylvite (KCl) and langbeinite ($K_2SO_4 \cdot 2MgSO_4$), the estimated potash reserves exceed 553 million tons. Based on freight cost advantages from the major sources in Saskatchewan, Canada, potash from New Mexico supplies product to companies in Texas, Oklahoma, Kansas, and Nebraska.

Production in the state is controlled by two companies – Mosaic and Intrepid. The Mosaic Company, formed in October 2004 through the combination of IMC Global and the Crop Nutrition division of Cargill, operates one facility in New Mexico with an annual recent production of about 1.5 million metric tons of MOP (based on sylvinite) and potassium magnesium sulfate (based on langbeinite). The associated 180,000 metric tons/year sulfate of potash (SOP) facility was sold to Great Salt Lake Minerals (GSLM) and subsequently closed. IMC then sold its potash/salt operations at the Great Salt Lake in Utah to GSLM's parent Compass Minerals.

In March 2004, Denver-based Intrepid Mining purchased the bankrupt Mississippi Chemical potash holdings in New Mexico for approximately $27 million. These facilities, now operated by Intrepid Carlsbad, comprise the West Facility and the East Facility plus a granular compaction plant, the North Facility, near the East and West Facilities (the former Eddy Potash operation remains closed). Intrepid uses flotation to produce red potash and hot-leach crystallization to produce higher-purity white potash. Refined product from the West Facility, a mine (800-1,100 feet deep) and refinery originally built by U.S. Potash in 1929 is transported to the North Facility compaction plant where the vast majority is converted to granular form and sold to agricultural fertilizer dealers and distributors. A portion of the production from the West Facility is sold directly as a standard grade product. Most of the red and approximately half of the white standard potash is converted to a granular product, which is used as a direct application fertilizer and in bulk blending of agricultural products. The balance of the white product is consumed in the specialty and industrial markets.

With the improved market for potassium products, the Intrepid East Facility was redesigned (improved recovery boosted the output to 370,000 metric tons of which 240,000 metric tons is converted to granular potash) and returned to a 24/7 schedule. All of the refined potash produced through hot leach crystallization at the East Facility is a standard form of white MOP (62 percent) and is marketed as Magna-K®, a high potassium-magnesium-sulfur specialty fertilizer based on langbeinite and used on chloride-sensitive crops such as citrus fruits (Harben and Barker, 2006).

PUMICE AND PUMICITE (Austin)

Pumice and pumicite are pyroclastic materials produced by the rapid expansion of dissolved gases in a viscous siliceous magma generally ranging from rhyolite to dacite composition. Pumiceous materials are inert to most chemicals and are composed primarily of SiO_2.

Williamson and Burgin (1960) reported that the SiO_2 content of 92 pumice and pumicite samples ranged from 54 to 77.6 weight percent with a median of 71.3 weight percent. This group of pyroclasts is distinctive because they are glassy and consist of a cellular structure composed of numerous thin-walled vesicles. Pumicite originates when dissolved gases in the viscous magma produce a froth or a large quantity of bubbles in a short period of time followed by rapid rupture of the vesicles. If fewer bubbles develop in the magma, and the glass vesicle walls are allowed to solidify rapidly enough to prevent collapse, then pumice will form.

Vesicles can range in size from less than 0.01 mm to over 20 mm but commonly range from 0.1 to 0.6 mm in diameter with equidimensional to highly elongate shape. Pumice has a white streak and a Mohs hardness of 6.0. The fracture is irregular, and the tenacity is generally brittle. Pumice usually has a silky luster whereas pumicite is more earthy (Hoffer, 1994). Pumice and pumicite are usually light colored, commonly light gray to white, but shades of light buff, brown, and pink are common. The density of the unexpanded glassy materials is about 2.5 g/cm^3 but, because of their cellular structure, the apparent density is generally less than 1.0 g/cm^3. Apparent density measurements of more than 250 pumice samples (Hoffer, 1989) show a range from 0.35 to 1.20 g/cm^3 with an average of 0.70 g/cm^3. Block pumice has commonly been used to refer to lump pumice; however, the term block has been defined legally as a pumice fragment possessing one dimension equal to or exceeding 50.8 mm (Federal Register, 1990).

Fragments of quartz, feldspar, hornblende, biotite, augite, and magnetite are commonly found as phenocrysts in pumice and pumicite. Generally, these minerals are most abundant in pumice with high apparent density.

All glasses are amorphous and are therefore unstable in nature over geologic time if in the presence of water. Pumice and pumicite are susceptible to alteration by chemical weathering at the earth's surface. Weathering of the pumice will devitrify the glass, form clay materials, and destroy the physical properties that make the pumice useful as an aggregate and abrasive. Therefore, fresh, unaltered pumice and pumicite are generally restricted to strata of late-Tertiary to Quaternary age or to older strata that has escaped alteration. Such areas occur in the western U.S. and include the active volcanoes of the Cascade Mountains in northern California, Oregon, and Washington. In addition, numerous deposits have been produced from siliceous calderas and volcanic dome complexes in California, Nevada, Arizona, New Mexico, and Idaho. New Mexico has ranked in the top five states in the production of pumiceous materials in the U.S. since 1980. Kansas has produced pumicite in relatively small amounts for many years.

U.S. pumice and pumicite production in 2006 of 1.58 metric tons was valued at about $50 million. In 2006, it came from 16 producers at 17 mines in 7 states. It was mined in Arizona, Oregon, Idaho, California, New Mexico, Nevada, and Kansas, in decreasing order of production. A survey of 58 deposits in the western U.S. shows that more than 30 percent contain no pumice fragments coarser than 19 mm. (Founie, 2007). The average percent of fragments sized greater than 19 mm for all of the deposits is 7.3 percent (Hoffer, 1994). The principal domestic uses of pumiceous materials include concrete admixtures and aggregates, building block, abrasives, laundry use, and landscaping. In 2006, about 82 percent of the production building blocks; 11 percent for horticulture; 3 percent for abrasives; 2 percent for concrete mixtures and aggregate; and 2 percent for concrete, landscaping, stone-washed laundries, and other applications (Founie, 2007).

New Mexico Pumice Deposits

The principal pumiceous deposits in New Mexico occur within the volcanic units related to the resurgent Valles caldera in the Jemez Mountains in north-central New Mexico (fig. 4). In the 1990s, production for four companies was 1,900 m^3/day from two Plinian ash-fall units: (1) the 0.17 Ma El Cajete Pumice of the Valles Rhyolite and (2) the 1.45 Ma Guaje Pumice Bed, within the Otowi Member of the Bandelier Tuff in Santa Fe, Sandoval, Rio Arriba, and Los Alamos counties (Hoffer,1994). Copar Pumice Company operates the El Cajete mine in sec. 5, T. 18 N., R. 4 E. and produces both locatable and saleable pumice (D. M. Bland, personal communication, March 28, 2007). In 2004, three other active mines were operated by Copar Pumice Company, Inc., CR Minerals Company, and Utility Block Company (Presley, 2006). All produced from the Guaje Pumice Bed. The Guaje Canyon Mine of Copar Pumice is in sec. 31, T. 20 N., R. 7 E., the Rocky Mountain Mine of CR Minerals is in sec. 33, T. 21 N., R. 7 E., and U.S. Forest Service Mine of Utility Block is in sec. 3, T. 17 N., R.3 E. According to the U.S. Geological Survey, these companies were operating in 2006 (A. Founie, personal communication, March 27, 2007).

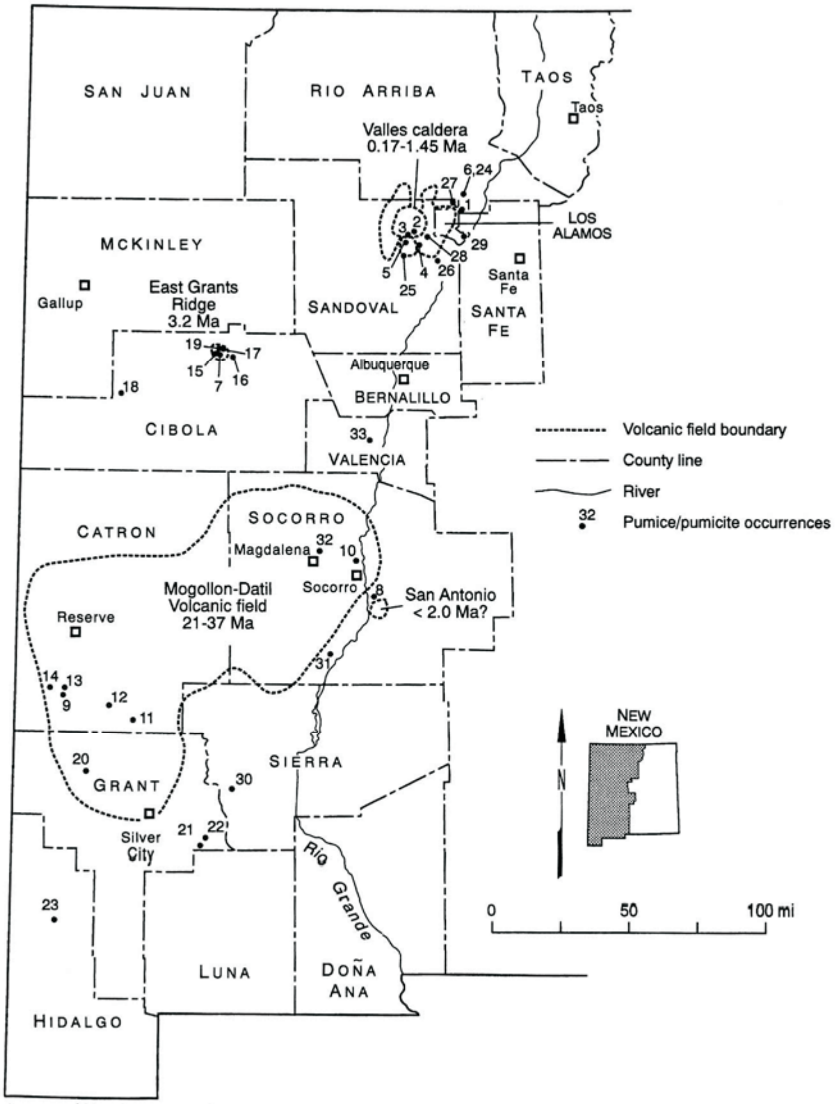

Figure 4. An index map showing the major pumiceous deposits and occurrences in New Mexico (after Hoffer, 1994). Numbered deposits are located and described in Tables 10 and 11 of Hoffer (1994).

Figure 5. Decorative medium-to-large stone, for use as accents, on display in a New Mexico stone yard (after Austin and others, 2006).

Physical properties of the New Mexico pumiceous materials indicate they are suitable for use in concrete aggregate, in Portland-pozzolan cements, and as abrasives. The coarse-particle pumice of the El Cajete Pumice is the most promising for laundry use. The laundry industry utilizes only coarse pumice ranging from 19 to 76 mm in diameter; fragments smaller than 19 mm would disintegrate completely before the completion of the 15- to 50-minute washing cycle. The proportion of coarse pumice in a typical pumiceous deposit is generally less than 10 percent.

SALT (McLemore)

Underground deposits of halite and sylvite are mined for the potash, and the salt is discharged during potash processing as a brine to tailing ponds and left to evaporate. Over the years, many feet of salt have accumulated. United Salt Corp. acquired the solar evaporation salt plant near Carlsbad in 1962 (United Salt Corporation, 2007). The salt is harvested on a 2,600 acre salt lake after the sun has evaporated the water from the brine. The salt is then carefully washed three times before it is packaged into a variety of solar salt products. Originally, the salt at Carlsbad was sold as deicing salt for roads. Today, the salt is used in water conditioning, agricultural feed products, chemical feed stocks, for swimming pool chlorine generation and numerous other industrial applications

SCORIA (Austin)

Scoria is a cellular, dark-colored volcanic rock of basic composition (commonly basalt or basaltic andesite). In industrial usage, scoria is also known as volcanic cinders. In addition to compositional differences, scoria differs from pumice in its darker color, higher density, coarser vesicles, more crystalline texture, and generally higher strength. Uses include natural lightweight concrete aggregate, road surfacing aggregate, and railroad ballast. As a constituent of lightweight concrete, scoria characteristically provides less weight reduction accompanied by higher strength than pumice (Williams, 1965). Cinder for these purposes must meet the same specifications as any other aggregate material, including abrasion resistance, immersion disintegration, and aggregate degradation. Cinders that qualify have a higher density than those used for lightweight concrete. The friable, fragmental nature of cinder deposits results in much lower production costs than from nonvesicular rock that must be crushed (Presley, 2006)

Scoria or volcanic cinder is formed when gases, especially water vapor, expand during a volcanic eruption. Scoria piles up around the vent, producing the scoria cone. The classic deposit is cone shaped with beds farther from the vent dipping outward and beds near the vent dipping inward. The actual shape of the deposit is determined by a number of factors, including wind direction and speed, vent shape, and lava viscosity.

Chemical analyses of samples collected at regular intervals from the vent zone to the perimeter zone show a progressive decrease in the ferric-to-total-iron ratio moving away from the vent. Ferric iron constitutes about 95 percent of the total iron in the vent zone and decreases to only 5 percent at the perimeter of the cone. No significant changes in other major element chemistries are observed.

Heat at the vent is postulated as the cause for oxidation. When black scoria samples were heated to 400°C in a muffle furnace, sample color began to change progressively after only one hour. Samples develop iridescent blue and green surface coatings after about 24 hours of heating; these samples resemble scoria found at intermediate distances from the vent. After about four days of heating, the color of the samples stabilizes at weak red or dark reddish brown. Tests run at 700°C showed the same color progression, but the colors stabilize at dark reddish brown after eight hours rather than the 84 hours required at 400°C. No color changes are noted in samples heated at temperatures lower than 400°C for a period of two weeks. In short, by heating scoria for variable amounts of lime, the vent-centered color pattern of a scoria cone can be duplicated. The typical pattern observed is dark-reddish-brown scoria in the vent zone, where maximum heat exposure occurs, brownish to dark-gray scoria at intermediate distances from the vent, and very dark gray to black scoria in perimeter zones, where volcanic ejecta are well insulated from the vent. As the demand for dark-reddish-brown scoria for landscaping aggregate expands, the value of being able to predict color variation in a particular deposit becomes more important (Osburn, 1982).

All U.S. scoria production comes from the western states plus North Dakota and Texas. In 2005, New Mexico contributed approximately 11 percent of U.S. production of about 2,960 metric tons annually (Willett, 2006). New Mexico's scoria resources are estimated to be 245 million m^3, near major roads and railroads. Scoria deposits, found in widely separated parts of New Mexico, are mostly associated with cinder cones of Quaternary age. Resources are exceedingly large.

Scoria blocks are an excellent building material, especially for institutions. Blocks made from scoria have greater structural strength than those made from pumice, mainly because of thicker cell walls in the rock. In addition, scoria blocks are sawable, nailable, vermin-proof, fireproof, have good insulating properties and are difficult to vandalize (Schmidt, 1957).

Noteworthy variations in form occur in many of New Mexico's scoria cones. Strong winds during the eruption produce reduced deposition on the windward side of the cone; the resultant lopsided form is common in the cones of the Potrillo volcanic field in south-central New Mexico. Twin Mountain in northeast New Mexico erupted from a fissure vent to form an elongate cone. Both sorting and grain size of the tephra reflect the sedimentary nature of the deposit. All volcanic ejecta emanate from a point source, the vent. Tephra in the vent are the largest and most poorly sorted in the deposit. Agglutinate also occurs in the vent area. In contrast, at the perimeter of the cone, scoria from each eruptive pulse is well sorted and graded. The average grain size is small, with the exception of an occasional block or bomb (Osburn, 1982).

The popularity of scoria as decorative stone in the desert landscaping industry is largely due to low maintenance and water requirements. The most common sizes of scoria used in landscaping are ¾-inch- and 1¼-inch clasts and large decorative blocks and bombs. Landscaping aggregate requires careful size and color control and thus commands much higher prices than scoria used for cinder block.

Cinders arc also used to sand highways to improve traction on icy surfaces. Cinders are typically crushed and screened to sizes from about -16 to +4 mm. Coarser particles can damage vehicle windshields, and finer particles can retain moisture and freeze in stockpiles or during transit.

Scoria blocks are also used as building stones. Uniformity of color is of importance in landscaping and decorative uses. Scoria lapilli are also used as an absorbent bed in gas cooking grills.

The large number of scoria or cinder cones in New Mexico and the relative ease of scoria mining make scoria an attractive source of lightweight aggregate. The majority of New Mexico's scoria output is used to make concrete to produce strong, lightweight cinder blocks. The second most important market for New Mexico scoria is as decorative stone used in desert landscaping and roofing material. Both of these uses require more control of color and size than the aggregate used for block manufacture; these controls create a higher price for landscaping and roofing scoria. Dense lava-flow materials that are waste products in the lightweight-aggregate industries are used for ballast and erosion control.

SILICA (McLemore, Barker)

Current mining of quartz/silica in southwest New Mexico is for decorative stone and railroad ballast. No silica flux is produced as of 2007.

Silica flux was produced from several quarries in Grant County for the Phelps Dodge mill. A silica flux mine also operated in the Little Hatchet Mountains near the Hidalgo smelter at Playas, but it closed when the Playas smelter closed in 1999. A silica flux mine in Luna County at Goat Ridge also has operated in the past, but is now closed.

STONE, DECORATIVE (Austin)

No classification can completely eliminate overlap between dimension stone, aggregate, and decorative stone because most stone is multi-purpose. Many used for decorative purposes are not produced specifically for that end use. Rock otherwise considered waste in dimension stone or aggregate quarries can be decorative stone coproducts. Many uses require a compromise between decorative and structural qualities (Bowles, M., 1992, written communication).

In 2006, the crushed stone industry, which includes aggregates, was valued at $13.1 billion and their products were produced by 1,200 companies operating 3,200 quarries, 85 underground mines, and 190 sale/distribution yards in all 50 states. Of the total crushed stone produced in 2006, about 70 percent was limestone and dolomite; 16 percent, granite; 8 percent, traprock; and the remaining 6 percent was shared, in descending order of tonnage, by sandstone and quartzite, miscellaneous stone, marble, volcanic cinder and scoria, calcareous marl, shell, and slate. It is estimated that of the 1.69 billion tons of crushed stone consumed in 2006, 32 percent was for unspecified uses, and 18 percent was estimated for nonrespondents to the U.S. Geological Survey canvasses. Of the remaining 850 million tons reported by use, 85 percent was used as construction aggregates, mostly for highway and road construction and maintenance; 13 percent for chemical and metallurgical uses, including cement and lime manufacture; 1 percent for agricultural uses; and 2 percent for special and miscellaneous uses and products (Willett, 2007).

Decorative stone, including ornamental stone, is more broadly defined here as any stone used primarily for its color, texture, and general appearance. It is not used primarily for its strength or durability, such as construction stone, or in specific sizes, such as dimension stone. The decorative stone industry uses a much wider range of stone types compared to stone that is dimensioned. Decorative stone usually serves some structural purpose, but is not load-bearing to any great extent. Weak or costly stones serve in decorative, not structural, applications (Austin and others, 2006).

Rough Stone

Rough stone is used as it is found in nature with very limited processing such as minor hand shaping, edge fitting, and size or quality sorting (Perath, I., 1992, written communication). This stone type is often marketed locally in relatively small tonnages and includes fieldstone and flagstone. The primary end uses of rough stone are landscaping, edging, paving, or large individual stone landscape or interior accents (fig. 5).

Fieldstone

Fieldstone is picked up or pried out of the ground (gleaned) without extensive quarrying and includes garden or large landscaping boulders (Austin and others, 1990; Hansen, 1969). Boulders and cobbles may be split or roughly trimmed for use in rubble walls and veneers, both interior and exterior. Popular fieldstone rock types include sandstone, basalt, limestone, gneiss, schist, quartzite, and granite, but many others are suitable. Much fieldstone is collected by individuals or small companies because the industry is labor intensive and markets are small. The stone may be sold locally in small quantities from the back of vehicles (Austin and others, 1990). Fieldstone includes many rock types, sizes, and shapes with the only common denominator that it must be set by hand and be durable (Power, W.R., 1992, written communication). In New Mexico, it is used for many similar uses including walls, wall facings, foundations and, in some cases, complete buildings. Fieldstone is picked or pried off the ground without extensive quarrying. Fieldstone includes moss-covered sandstone, cobbles and boulders of basalt, limestone, gneiss, schist and granite. The most productive fieldstone operations in northern New Mexico are near Las Vegas, Ribera, San Miguel, and Tecolote where extensive deposits of Triassic and Permian flagstone and moss-covered sandstone occur. The majority of stoneyards and landscapers in northern New Mexico have stockpiles of fieldstone, garden or landscaping rock that have been obtained locally. Fieldstone production in New Mexico is difficult to estimate, but is large in value and tonnage.

Moss rock. Moss rock is fieldstone partially covered by algae, mosses, lichens, and fungi that give the rock an aged and variegated patina (Austin and others, 1990). The plants are supported by moisture and nutrients in the stone. Moss rock is used for landscaping, walls, and fireplaces. Although almost any durable rock can be a moss rock, most are slabby or rounded sandstone and limestone. Moss rock, a popular sandstone, is found throughout the flagstone areas where it occurs as loose fieldstone on surface outcrops. Moss rock is also collected near Cuba, New Mexico. It usually is partially covered with plant growth that gives the rock an aged patina. Moss rock is used for landscaping, retaining walls and fireplaces.

Flagstone

Flagstone or flagging consist of thin irregular slabs used for paving, walkways, and wall veneers. Random-shaped flagging is produced widely in the U.S. Suitable stone breaks very easily in one direction producing flags. Any fissile stone can be used, but sandstone (bedding planes) and slate (cleavage surfaces) are best. Sandstone flags up to 0.5 m^2 can be split to a thickness of 3 cm or less. Flagstone slabs 3 to 10 cm thick are used for walkways in high-traffic areas and must be resistant to abrasion. If used in walkways, these thin slabs must be set on a very firm base. Thicker flags of sandstone or granite may be used in walls or set on edge as curbing.

Although flagstone can be produced in New Mexico from sedimentary rocks like sandstones, limestone and dolostones, most sandstone used by the building industry is quarried near Las Vegas, Ribera, San Miguel, Anton Chico, and El Rito. The flagstone and dimension stone here are of Permian and Triassic-age. They easily split into smooth flagging of 3- to 5-cm-thick slabs and blocks of various sizes in colors varying from white to brown to red. The Anton Chico quarries are noted for their white-to-buff sandstone. The Abiqui-El Rito quarries produce flagging that is primarily buff to brown. Flagstones of various reds are widely produced in the Ribera, San Miguel, Las Vegas, and Tecolote areas. Flagstone rubble and moss rock from local quarries and fieldstone sites are hauled to nearby major cities and sold to contractors and the general public directly from pickup and flatbed trucks.

Aggregate

Uncrushed stone

Natural aggregate is lightly processed, usually by washing or screening, yielding products suitable for decorative use. Fragments can be either rounded or angular and must be durable. Many types of decorative stone can be used for rock lawns or area covers in virtually unlimited colors. Typically, local materials are used which limits choice but lowers cost. The aggregate is placed on UV-resistant black, impermeable or semipermeable polyethylene (4 mil) covering a prepared surface treated with weed killer. A wide variety of sizes are used at an application rate of at least 50 kg/m^2 that varies depending on aggregate size. Some special categories of uncrushed stone are described below.

River rock. A distinctive attribute of river rock is the water-rounded pebbles, cobbles, and boulders, commonly used as an area cover. White to gray is typically specified, but other colors are available. River rock most commonly is granite or gneiss, but any durable rock may be used. In Pennsylvania, white to buff vein quartz is a popular river rock for landscaping (Berkheiser, S.W., Jr., 1991, written communication).

Scoria and cinder. Scoria or volcanic cinder is a lightweight, vesicular equivalent of basalt or other basic volcanic rocks. It is used primarily for desert landscaping in the southwestern U.S. and is less common elsewhere, but is available in most parts of the country. Scoria is sold as either red to brown or black to gray varieties, but both are otherwise similar. Reddish hues are more popular, and hence, more valuable than other hues (Osburn, 1980). Color differences of cinder is a result of the presence (red) or absence (black) of oxygen during volcanic eruption and emplacement. In northern New Mexico, Tertiary and Quaternary basaltic rocks are exposed for hundreds of square miles near Grants, Albuquerque, Santa Fe, Española, and Taos where large quantities of basaltic stone have been produced. Great volumes of basalt and scoria are in volcanic terrains east and west of the Sangre de Cristo Mountains. Major outcrops are at Caja del Rio, Black Mesa, West Mesa and the Taos Plateau. The majority of basalt is on federal land, so permits for removal must be obtained. South-central New Mexico south of Las Cruces contains a number of cinder cones that supply the building and landscaping industries (Austin and others, 1998). The area produces both red and black, fine-to-coarse-size cinder, heavy, brown-and-black, coarse-to-fine cinders, and coarse-to-fine charcoal-to-russet cinder. One company reports more than 50 percent goes outside New Mexico, mostly states to the east. Only about 10 percent is sold for local consumption.

Scoria is a lighter weight, less dense, vesicular equivalent of basalt. It is used mainly in cinder blocks and for landscaping. Other uses are as dimension stone, lava rock in barbecues and anti-skid material on icy highways.

Basalt, fine-grained, hard, tough, dense and durable rock, is produced from volcanic terrains principally in northeast New Mexico near the Rio Grande in the center of the state. It is well suited for use as aggregate, dimension stone, railroad ballast and riprap. At present near Las Cruces basalt is mainly obtained from the many State Highway Department pits where the rock is quarried and sized for road aggregate. The proximity of basalt to major cities in the south allows use of rough and rounded basalt in walls and wall facings, and in landscaping.

Fused Argillaceous Rock. Natural fires in New Mexico lignite produce fused interbedded claystone and sandstone locally called “red dog.” This material is used in the same manner as volcanic cinder, most commonly as road-building material in coal mines.

Crushed stone

Crushed stone is the most common decorative aggregate and can be produced from virtually any pleasing stone. It is broken mechanically and usually screened prior to use; larger sizes are often called rubble. Harris (1991) uses the term “decorative aggregate” to describe crushed and sized stone used for landscaping such as area cover, rock lawns, walkways, and borders around plants or gardens. Exposed aggregate, dash, and terrazzo (all defined below) are included by us under crushed stone, although they are used with a binder such as cement.

Rubble. Rubble consists of large rough stone or blocks produced in quarrying, often as waste, used for retaining walls, seawalls, bridgework, and landscaping. Only landscaping rubble is considered decorative stone because it is used primarily because of color, texture, or general appearance. In New Mexico, large boulders of pegmatite are used as landscaping pieces (Austin and others, 1990). In New Mexico, property walls composed of rubble are relatively common, particularly in southern New Mexico near the Vado stone quarry south of Las Cruces.

Smaller rubble is popular as wall facing in homes and commercial buildings. The primary purpose is aesthetic--it replaces brick or other veneer--but ease of installation, weather resistance, lightweight, and ability to bond well with mortar are also important. Rubble may be set in random patterns from about 0.05 to 4 m^2 of exposed rock. Low-density rock, such as pumice, has several advantages. Shipping costs are lower, setting is easier for the stonemason, and few if any anchors are required to tie the stone veneer to the wall (Power, 1983).

Exposed aggregate. Exposed aggregate is one of the most common methods to use crushed stone. Stith (1970) found the most important properties to be color, hardness, soundness, absorption, shape, size distribution, and impurities.

Many colors and shapes are possible making exposed aggregate compatible with almost any architectural scheme. Color should be uniform and permanent because it is the main criterion used by architects. Observation of weathered and fractured outcrops of the proposed aggregate can be very useful in determining how the stone will react (Cutcliffe and Dunn, 1967). Spalling and other forms of physical deterioration should be noted. The color should vary only slightly, if at all, between weathered and fresh outcrops. Variations in color, based upon exposure to sunlight or weather, should be noted to minimize color differences across the sides of a structure (Cutcliffe and Dunn, 1967). Color segregation of stone by quarry procedures, blasting, stockpiling, blending, batching, and due to weathering or lithology should be avoided (Cutcliffe and Dunn, 1967).

The ability to cast exposed aggregate in complex shapes and with background coloring (dash) of cement give the architect great freedom. Aggregate, mixed with white or gray cement in a 2:1 ratio, can be precast into panels, or cast in place in walls and floors or walkways, with the aggregate dispersed or concentrated in the facing layer (Stith, 1970). The aggregate is exposed by subjecting the surface of the aggregate/cement mixture to sand blasting, bush hammering, wire brushing, or acid washing (Cutcliffe and Dunn, 1967) and it is finally sealed.

Dash. Dash, either coarse (for texture) or fine (for color), is added to exposed aggregate, stucco or concrete for texture or color. Sand dash is added to stucco for color and a small-scale exposed aggregate surface. Very fine dash is added to concrete or cement as a permanent pigment instead of more expensive mineral pigments which may react with the cement compounds. Non-reactive dash material, which is well mixed, avoids blotchiness or shade variation common with artificial or mineral pigments and may be used in conjunction with stucco dash or exposed aggregate. No dash is currently produced in New Mexico.

Terrazzo. Produced by the Romans over 1,500 years ago, terrazzo floors provide quality, at low original and maintenance cost, and very long life. Terrazzo, a mixture of sized, crushed stone, and cement, offers variety in color and design. This mixture is poured into a prepared floor area and after hardening, ground smooth, sealed, and often polished (Reed, 1978). The stone aggregate has low porosity and low absorption. The portion of the terrazzo that needs protection is the portland cement matrix, which is porous and absorbs stains. The primary application of terrazzo is in high traffic, public areas, and buildings. Relatively soft stone, usually limestone, dolostone, or marble is preferred, but granite is also used. Quality control is paramount during quarrying, so that color can be matched through repeated batching, and during processing, so quality, color continuity, and freedom from impurities are assured. The Terrazzo Tile and Marble Association of Canada recommends a thin-gauge epoxy or polyacrylate for sealing. Most terrazzo in New Mexico is present in large government and commercial buildings in larger cities.

STONE, DIMENSION (Austin)

Dimension stone consists of blocks, slabs, or sheets of stone which are either sawed or chipped to specific dimensions for structural, ornamental, or monumental uses. In the past, dimension stone was used extensively as building blocks to support the full weight of the structure. More recently, however, supporting structures have been mainly of steel or reinforced concrete, and stone is used chiefly as a decorative veneer. Some dimension stone is used in constructing ashlar masonry walls, and also for decorative purposes as ornamental stone, including panels for interior and exterior walls, window sills, mantels, and tops for furniture and lavatories. There is also a continuing demand for dimension stone for use as monuments in cemeteries (Lindvall, 1965).

Dimension stone can be developed from a variety of rock types including sandstone, limestone, marble, travertine, quartzite, granite, basalt, and related igneous rocks. The type of rock is commonly not as important as is the color, durability, texture, and freedom from flaws. Deposits of rock should be large enough to develop a sizable quarry, and thickness of overburden should not be excessive.

In 2006, approximately 1.5 million tons of dimension stone, valued at $275 million, was sold or used in the U.S. Dimension stone was produced by 100 companies, operating 136 quarries, in 35 states. Approximately 38 percent, by tonnage, of dimension stone sold or used was limestone, followed by granite (27 percent), marble (14 percent), sandstone (13 percent), miscellaneous stone (7 percent), and slate (1 percent). By value, the leading sales or uses were for granite (39 percent), followed by limestone (35 percent), sandstone (9 percent), marble (7 percent), miscellaneous stone (6 percent), and slate (4 percent). Rough block represented 64 percent of the tonnage and 54 percent of the value of all the dimension stone sold or used by domestic producers, including exports. The leading uses and distribution of rough block, by tonnage, were in flagging, exports, and unlisted and unspecified applications (36 percent) and construction (34 percent). Dressed stone mainly was sold for flagging (27 percent), curbing (24 percent), and ashlars and partially squared pieces (17 percent), by tonnage (Dolley, 2007).

New Mexico Dimension Stone

In 2007, only commercial marble (travertine) was produced as dimension stone. New Mexico Travertine (NMT) of Belen, New Mexico, produces travertine from quarries on Mesa Aparejo (secs. 12 and 13, T. 5 N., R. 3 W.). These quarries were operated intermittently prior to NMT operations along with several others along the Comanche thrust between the Sierra Ladrones and New Mexico Highway 6 (NM-6). Cooper (1964) conservatively estimated that the NMT quarries contained reserves of about 45 million ft^3 of associated types of commercial-quality travertine and altered limestone. Travertine of all types underlies about 1,140 acres and may total about 200 million short tons in place (Barker, 1988).

Commercial marble is any crystalline rocks composed predominantly of calcite, dolomite, or serpentine that is capable of taking a polish (Meade and Austin, 2006). Marble is probably the oldest term used for dimension stone. In ancient Rome, the root word for marble—marmore—was used for all hard stones that could be polished. The same practice is followed in Italy today where the term “marble” is used for all hard stone that will take a polish, including granite. The practice is not followed in the U.S., where commercial marble encompasses true marble in the geologic sense as well as many crystalline limestones, travertines, and serpentine, but not other lithologies.

Travertine is widespread in New Mexico (Kottlowski, 1965; Barker and others, 1996). Other large occurrences near the NMT quarries are west of Sierra Ladrones (Barker, 1983) and at Mesa del Oro (Jicha, 1956, 1958). About 50 discrete deposits are reported in the literature

(Barker, 1986, 1988) with many additional unreported occurrences in the extensive limestone terrains of southeastern New Mexico. Most deposits are associated with the extensional Rio Grande rift or on the Jemez volcanic zone that intersects it. The extensional volcanic terrane in the Basin and Range province of southwestern New Mexico also has numerous deposits.

New Mexico Travertine

NMT is one of three dimension-stone operations producing travertine in the U.S.; the other two are in Idaho and Montana. NMT quarries stone from extensive, well-bedded, laminar lenses of travertine just east of Mesa Lucero in the eastern foothills of Mesa Aparejo. The quarries are about 25 miles west of Belen in on BLM and private lands.

General geology of Mesa Aparejo. Limestone of the Pennsylvanian Madera Formation in the subsurface to the west is probably the primary source rock for the calcium-rich, CO_2-charged water that formed the Quaternary travertine at the edge of Mesa Aparejo. The lower 800 ft of the Madera Formation are well exposed just west of the NMT travertine quarries (Kelley and Wood, 1946; Cooper, 1964) and probably represent the Gray Mesa Member of the Madera (Kues, Lucas, and Ingersoll, 1982). The large northeast-trending Comanche fault mostly west of the travertine was mapped as a normal fault dipping 70° east by Cooper (1964). The fault and associated minor faults acted and continue to influence circulation of CO_2-charged ground water and spring water. At Mesa Aparejo, travertine was deposited as extensive, thick, laminar lenses. Just north of the mesa (secs. 35 and 36, T. 6 N., R. 3 W.), travertine presently being deposited from springs illustrates one way older and larger deposits may have formed.

The varieties of travertine at Mesa Aparejo are distinguished by color and structure, but the mineralogy and origin are fundamentally the same for each. Bedding is commonly laminated with characteristic serrations probably representing the forward surface of a micro-terraced rimstone dam which impounds a pool of spring water that deposits limestone. Concretionary masses of various dimensions are largely due to algal activity. Rod-like structures, frequently upright and clustered in tufts or masses, may be in part algal or bacterial when microscopic, but most likely represent deposition around grass, stems, or branches. Holes within travertine may result from rapid accumulation over tufted or dimpled surfaces, gas bubbles encrusted by travertine, or voids produced by primary deposition of soluble salts later removed by dissolution. Shrub-like forms, composed of upward-radiating bacterial clumps in $CaCO_3$ (Chafetz and Folk, 1984), are locally abundant.

The highly variable color of the Mesa Aparejo travertine is a result of impurities (fig.6). Pink and red are probably primary and are due to inclusion in the travertine of red iron oxide from nearby Permian sandstone, siltstone, and shale. Yellow and brown are secondary and were produced close to the surface by percolating oxidizing waters during case hardening and weathering of the travertine.

Figure 6. Scheherazade quarry at New Mexico Travertine quarries west of Belen, New Mexico. Diamond-impregnated belt saw in operation cutting 1½-inch channel as deep as 10 ft. Wire saw is "pulling the floor" on block previously cut by belt saw. Photograph courtesy of Rocky Mountain Stone.

Onyx is translucent calcium carbonate in which layers parallel the surfaces of infilled voids or laminae, and is intimately associated with travertine. Most onyx, now calcite, was deposited originally as aragonite, a metastable higher-temperature form of calcium carbonate. Local coarse-grained aragonite is associated with spring orifices mainly in the Apache Golden Vein portions of the Gray Mesa Member of the Madera Formation. Because aragonite is more soluble than the calcite, advanced dissolution forms soft crumbly zones and large voids later filled with clay or mud (Cooper, 1964).

Commercial varieties of NMT travertine. NMT produces commercial varieties of stone including *Sunset Lite* (creamy-white travertine), *Scheherazade* (pale-cream to pink travertine with onyx;), *Navajo Gold* (yellow to brown travertine with minor onyx and lilac- or pinkish-gray sections), *Vista Grande* (dark reddish-brown to cream travertine with onyx), *Desert Gold* (yellow-gold with abundant onyx), and *Apache Golden Vein* (altered stylolitic yellow to reddish-gray limestone). Production of several sub-varieties is possible by cutting different directions in relation to bedding of the travertines. A "vein cut" cross cuts bedding; a "fleuri cut" parallels bedding. In 2007, *Navajo Gold* is NMT's premier light-colored commercial stone. NMT ships about 100 short tons of travertine per month. This amounts to about 15 percent the operation's total business. The rest is finished stone from blocks purchased from other quarries. In the spring of 2007, NMT's chief market area was Florida. In the past it has been Chicago and/or Los Angles (T. J. Lardner, personal communication, March 27, 2007).

By varieties, the order of 2007 sales is (1) Navajo Gold (produced as fleuri cut only), (2) Scheherazade (vein cut only; but fleuri cut for split-face ashlar), (3) Apache Golden Vein (vein cut in slabs only), (4) Desert Gold (both vein and fleuri cut; slabs only), (5) Vista Grande (fleuri cut only), and (6) Sunset Lite (both vein and fleuri cut, and also as random broken material). The six varieties of travertine mined by NMT vary in detail within a given layer but are laterally consistent for hundreds of feet. Several additional varieties of travertine have been identified in the Mesa Aparejo area but have not been quarried. Such a wide variety of types within one travertine deposit is very unusual (T. J. Lardner, personal communication, March 27, 2007).

Dimension stone is produced by cutting, fabricating, or selecting stone for specific shapes or sizes. It has become popular in rubble walls, fireplaces, patio floors, and as flagstones, especially where decorative accents and special architectural effects are desired (Austin and Barker, 1990). In addition to stabs, New Mexico Travertine markets ashlar, rubble, and crushed stone. The ashlar and rubble are most commonly used in walls. Crushed stone is used for landscaping. In this way, very little of NMT's travertine is waste.

Rocky Mountain Stone Company (RMS) markets stone for NMT in New Mexico. Finished travertine is displayed at the RMS stoneyard in Albuquerque. Some travertine is shipped to sculptors for carving or to marble shops and dealers primarily for distribution to furniture manufacturers. RMS aggressively markets their products in many parts of the U.S. and has sold large quantities of stone in such distant states as New Jersey and Washington. RMS travertine products are now beginning to penetrate international stone markets as well.

New Mexico Dimension Stone Produced in the Past

Most parts of New Mexico contain deposits of marketable stone, and small quantities of stone have been produced from many of these deposits. Quarries from which stone for highway construction has been obtained are for the most part not located on this map, due to the transient nature of most of these operations.

Dimension stone was produced at the Gallinas mine, northeast of Las Vegas in San Miguel County, which marketed monumental and ornamental granite in northeastern New Mexico. Also near Las Vegas, the Mavalo mine produced flagstone. A quarry in Marble Canyon about three miles east of Alamogordo in Otero County in south-central parts of the state that contained a 30-foot-thick bed produced marble for a variety of uses. A cream-colored sandstone (Glorieta Sandstone) was quarried near Lamy in Santa Fe County in north-central New Mexico and has been used in the construction of some public buildings in Santa Fe. Dark-red, gray, and brown sandstones from quarries west of Las Vegas have been used in buildings at New Mexico Highlands University. Other quarries in various parts of the State have produced small quantities of stone for local use.

ZEOLITE (Barker)

Zeolites are aluminosilicates, composed of a three-dimensional crystal lattice with loosely bound cations, able to hydrate and dehydrate without altering their crystal structure (Holmes, 1994). Zeolites have fixed pore sizes and active sites in the crystal lattice. The main commercial uses for zeolites is exchanging ions, absorbing gases, vapors and liquids, acting as molecular-scale sieves (Breck, 1974), and catalyzing reactions. About 48 natural zeolites and 100 synthetic zeolites exist (Eyde and Holmes, 2006). Clinoptilolite (clino), the main commercial natural zeolite, is in geologically young volcanic ash altered by alkaline groundwater in the western U.S. Synthetic zeolites are used in small tonnages for molecular sieves and catalysts. Zeolite production in the U.S., is on the order of 50,000 short tons per year from Arizona, California, Idaho, New Mexico, Nevada, Oregon, and Texas (Eyde and Holmes, 2006).

This paper draws heavily from Bowie and Barker (1986), Bowie and others (1987), White and others (1996), Austin and Bowman (2002), Bowman (2003), Freeman (2003) and Barker and others (2004).

Clinoptilolite Uses

The physical, chemical and mineralogical characteristics of clino yield many commercial applications. While adoption of zeolite technology has been slow in the U.S. compared to other regions of the world, continued testing and research has shown a wide range of uses.

The clino produced by SCM and others is used, horticulture and soil amendments, water treatment, floor dry, aquariums, aquaculture and pond filtration, air and liquid filters, pollution control media, and industrial fillers. It is used in animal hygiene and animal feed at confined animal feeding operations (CAFOs) and for CAFO odor control. Zeolites are inert, non-toxic substances federally classified as generally regarded as safe (GRAS) in most applications. They are exempt from most regulations and reporting when used in accordance with good agricultural practice and when they comprise less than 2 percent in animal feed products (40 CFR, Part 180.1001 and elsewhere).

Other applications for natural zeolites include paper and paint fillers, thermal storage, natural gas purification, ground water and sewage effluent treatment, and removal of ammonia, heavy metals and radioactive ions from industrial and municipal effluents.

Clino is used to remove cations from solutions. Surface modified zeolite (SMZ) is a sorbent for removal of anions and neutral organics from water. Specific clino applications are control of chemical pollution in groundwater, removal of organic compounds from oil field waters, and elimination of pathogens from sewage effluent. Combining the sorption capabilities of SMZ with chemical or biological transformations can yield complete removal of toxic materials from contaminated water.

St. Cloud Mining

St. Cloud Mining (SCM) accounts for about 60 percent of domestic production zeolite from a clinoptilolite (clino) deposit in south-central New Mexico. The clino deposit currently mined by SCM is about four miles south of Winston in south central New Mexico, (Bowie and others, 1987). The major physical and chemical specifications of SCM clino are in Table 7. The mineral content by weight is 74 percent clino with varying amounts of quartz, feldspar, and clay but no fibrous minerals. The SMZ operation is in sections 2–3, 10–11, 14–15, 22, T. 12 S., R. 8 W. It is at the southern end of the Winston graben in altered volcanic ash about 29 Ma (McIntosh and others, 1991). Sales in 2006 for SCM clino were about 31,500 short tons distributed as follows:

• Animal hygiene	25 percent
• Animal feed	23
• Horticulture	17
• Water treatment	15
• Floor dry	13
• Aquarium	4

• Air filtration	2
• Filters	1
• Odor control	<1

Table 7. Various physical and chemical properties of St Cloud clinoptilolite in both English and metric units (modified from White and others, 1996).

Parameter	Value
Acid stability	0–7 (pH)
Alkali stability	7–13 (pH)
Bulk density (solid, dried)	1393 kg/m^3 (87 lbs/ft^3)
Bulk density (aggregate, dried)	
4x6 mesh	849–913 kg/m^3 (53–57 lbs/ft^3)
4x14 mesh	865–929 kg/m^3 (54–58 lbs/ft^3)
14x40 mesh	993–1057 kg/m^3 (62–66 lbs/ft^3)
Cation exchange capacity (CEC)	1.0–2.2 meq/gm (1.2 typical)
Color	White 85 optical reflectance
Crushing strength	69 kg/cm^3 (2500 lbs/in^3)
Hardness	3.5–4.0 Mohs scale
Molecular ratio	4.9 (Si/Al)
Other	Negligible solubility Non-slaking Free-flowing Readily mixable
pH (natural)	8.0 (approx.)
Pore size (diameter)	4.0 Å
Pore volume	15 percent
Resistivity	9000 (approx.) ohms/cm
Specific gravity	2.2–2.4
Surface area	40 m^2/gm
Swelling index	Nil
Thermal stability	650°C (1202°F)

Approximately 35 percent of all SCM clino products are bulk sales, with the remaining 65 percent of products packaged. SCM clino prices vary depending on particle sizing, packaging, quantity and quality-control requirements and range from \$0.02 to \$0.20 per lb (\$40-\$400 per st) for standard products. The majority of sales are to manufacturers rather than the final end-user. SCM ships clino products throughout the U.S. as well as to customers in Canada, Mexico, and overseas. Other zeolite deposits in New Mexico include Buckhorn Foster Canyon and others (Bowie and others, 1987).

SCM mines commercial clino at the surface mostly in the fall and winter when it is dry. SCM employs about 25 at the mine and plant. Unconsolidated sand and gravel (a co-product) above the clino is removed using a bulldozer, front-end loader and trucks. The upper surface of the clino is blown clean using compressed air. The bed is then drilled, gently blasted, and the clino is loaded and transported about 1.2 miles to the SCM mill. The clino is crushed, dried, and screened to various sizes and packaging as specified by customers. No other beneficiation or treatment of the clino occurs prior to sale.

Since 1996, the entire SCM production goes directly to its customers by truck, except for some of the product going overseas. This latter material is place in containers at the plant for rail shipment and then trucked to El Paso, Texas, where it is loaded onto flatbed rail cars. The SCM operation is not as remote as it first seems. It is close to I-25 and New Mexico is a backhaul state for trucks (more is trucked in than trucked out). Thus, trucks are the exclusive transport method since the mid-1990s.

SCM has five separate bagging and three bulk bag lines. They produce standard, private label and custom packaging (bags, boxes, plastic or paper) in one pound to one ton sizes with stitched, heat seal or valve closures in a wide range of options. On-site warehouses, for packaged products, have a storage capacity of 2,000 tons and incorporate four loading docks that can serve either van trailers or flatbeds. Drive-under bulk truck loadout is also available. Bulk packaging in approximately 1-ton and other supersacks or directly loaded in any bulk truck or rail car configuration including top loading or pneumatic carriers (Austin and Bowman, 2002).

POSSIBLE PRODUCERS

Garnet (McLemore, Barker)

Garnets are a group of silicate minerals common to skarns and igneous rocks and are the general name for a group of complex silicate minerals with similar crystalline structures and diverse chemical compositions. The general chemical formula is $A_3B_2(SiO_4)_3$, where A can be calcium, magnesium, ferrous iron, or manganese and B can be aluminum, chromium, ferric iron, or rarely, titanium. Angular fractures, high hardness, and an ability to be recycled characterize industrial garnet. The complex mineralogy of garnet determines its utility for a variety of uses, including water filtration, waterjet cutting, abrasive, in sand blasting media, and water filtration.

Garnet deposits must be large enough to sustain production for 10–20 years, contain the right type and size of garnet for the end-user, be easily and inexpensively processed, and be close to markets and/or transportation routes. The U.S. produces approximately one-third of the world's production of garnets; in 1996, six companies produced 68,200 tons of crude garnet from mines in the U.S. (Balazik, 1997).

Although garnet has not been produced in New Mexico in 1998–2000, at least one company is reported to be exploring for garnet in 2007. Garnet exploration in recent years has mainly centered on two areas. The San Pedro mine south of Taos, and the Orogrande area south of Alamogordo.

The San Pedro mine, which reportedly has 3.5 million tons of garnet reserves available for underground mining, was acquired by Canadian interests in the early 1990s. Local opposition to the project forced delays that eventually led, along with status problems, to failure to acquire a Sante Fe county permit.

Large reserves of garnet crops out on claims just west of Orogrande in Otero County (Lueth, 1996). These deposits were drilled and sampled in the late 1990s to early 2000s, but no significant development occurred.

Garnet typically is found in skarn deposits in southern and central New Mexico and in some areas, garnet is a major constituent of waste rock piles remaining after recovery of metals (Lueth, 1996). For example, approximately 149,000 short tons of 20–36 percent garnet are estimated to occur in four tailings piles at Hanover (Cetin and others, 1996). Average values for crude garnet concentrates ranged from approximately $55 to $120 per ton in 1999 (Olson, 2000).

Beryllium (McLemore)

Only one beryllium mineral, bertrandite, is currently mined in the U.S.; bertrandite contains less than one percent Be. Beryl also has been mined in the U.S. in the past and contains approximately 4 percent Be. Brush Wellman Inc., Cleveland, OH, mines bertrandite at Spor Mountain near Delta, Utah. Recent exploration for beryllium in New Mexico has occurred at Iron Mountain, Sierra County and in the southern San Mateo Mountains in Sierra and Socorro counties where bertrandite is found in contact-metasomatic deposits in recrystallized limestones and veins in volcanic rocks. Results of exploration are unknown. Bertrandite also is found in veins in the Taylor district north of Iron Mountain in Alamosa Canyon area in Socorro County. Exploration permits have been denied by New Mexico Mines and Minerals Department partly because the ore is found along structures that also control hot and cold springs feeding the Alamosa Canyon.

Heavy Sands (McLemore)

Heavy mineral, beach-placer sandstone deposits are concentrations of heavy minerals that formed on beaches or in longshore bars in a marginal-marine environment (Houston and Murphy, 1970, 1977). These deposits in New Mexico are found in Cretaceous rocks, mostly in the San Juan Basin and are small (<3 ft thick), low tonnage, and low grade. Many beach-placer sandstone deposits contain local high concentrations of Th, REE (rare earth elements), Zr, Ti, Nb, Ta, U, and Fe. Detrital heavy minerals comprise approximately 50-60 percent of the sandstones and typically consist of titanite, zircon, magnetite, ilmenite, monazite, apatite, and allanite, among others. They rarely exceed for more than several hundred feet in length, are only tens of feet wide, and 3-5 ft thick. However, collectively, the known deposits in the San Juan Basin contain 4,741,200 tons of ore containing 12.8 percent TiO_2, 2.1 percent Zr, 15.5 percent Fe and less than 0.10 percent ThO_2 (Dow and Batty, 1961). Minor exploration has recently occurred for these deposits mostly for Ti, but the small size and difficulty in recovering economic minerals will continue to discourage development of these deposits in the future.

Nepheline Syenite (McLemore)

Nepheline syenite is a light-colored, medium- to coarse-grained holocrystalline, silica-deficient feldspathic plutonic igneous rock largely made up of nepheline, sodium feldspar (albite), alkali feldspar (orthoclase, miocrocline) but no quartz. Nepheline syenites are essentially syenites that are undersaturated in silica.

The Addwest Minerals Wind Mountain nepheline syenite project in southern Otero County is for sale. The nepheline syenite was to be used for a constituent in amber-colored beverage containers, ceramics, and flat glass (McLemore and Guilinger, 1996; McLemore and others, 1996). The nepheline syenite contains high iron compared to other commercial sources of nepheline syenite, but, when the Wind Mountain nepheline syenite is crushed and passed through a specialized rare-earth magnet, the resulting nonmagnetic product is similar in composition to Grade B product specified by Unimin Canada Ltd. The magnetic fraction can be sold as millite, an iron-rich additive required for controlling the color of glass. Several other consumers have tested the nepheline syenite and found it suitable for use in ceramics, fiberglass, and flatglass. The lack of free silica as quartz also enables use of the Wind Mountain nepheline syenite as a silica-free abrasive. Interesting textural variations in the main mass of the syenite, wisps of finer grained material waving through the rock, also make it an attractive building stone. Mining will be by underground, room and pillar methods. An adit was started in early 1995. Processing will involve crushing, grinding, magnetic separation, and screening. At full production, Wind Mountain is expected to process 3,000 short tons per day or 700,000 short tons per year. Current proven, probable, and inferred reserves total 200 million short tons for a mine life of more than 100 years.

Alunite (McLemore)

Alunite is a potential source of aluminum and has been mined in several places in the world for its aluminum content (Hall, 1978; Hall and Bauer, 1983). Nearly all of the aluminum used in the U.S. comes from 38 foreign sources, primarily from bauxite deposits (U.S. Bureau of Mines, 1992). During World War I, alunite was used as a source of potassium fertilizer. In the 1960s, the Soviet Union produced alunite for its aluminum content; potassium sulfate and sulfuric acid were recovered as by products (Hall and Bauer, 1983). Alunite is one end member of a series of sulfates that occur in several geologic environments, all of which require base leaching of the host rock by acidic fluids. Minerals of the alunite group have the general composition AB_3 $(SO_3)_2$ $(OH)_3$ where A is typically K+, Na+, Pb++, NH_4+, or Ag+ and B is typically Al+3 or Fe+3 (Brophy, and others,1962). Nine of the more common species are (Brophy and others, 1962; Altaner and others, 1988):

- Alunite—$KAl_3(SO_4)_2(OH)_6$
- Natroalunite—$NaAl_3(SO_4)_2(OH)_3$
- Ammonioalunite—$NH_4Al_3(SO_4)_2(OH)_6$
- Jarosite—$KFe_3(SO_4)_2(OH)_6$
- Natrojarosite—$NaFe_3(SO_4)_2(OH)_6$
- Ammoniojarosite—$NH_4Fe_3(SO_4)_2(OH)_6$
- Argentojarosite—$AgFe_3(SO_4)_2(OH)_6$
- Plumbojarosite—$PbFe_6(SO_4)_2(OH)_6$

Solid solution between the species is common.

Alunite is found in five areas in New Mexico:

- Old Hadley district volcanic epithermal vein deposits (McLemore and others, 1996)
- Alum Mountain
- Steeple Rock
- Vicks Peak, San Mateo Mountains
- Chino porphyry copper deposit

Alunite typically occurs with a variety of minerals including quartz, kaolinite, jarosite, pyrophyllite, and iron oxides. Pure alunite deposits are not found in New Mexico. However, local zones contain as much as 30 percent alunite in the Alum Mountain and Steeple Rock districts (Hall, 1978).Age determinations of alunite suggest two periods of formation: alunite associated with volcanic-epithermal veins is between 28 and 33 Ma (McLemore, 1996); alunite associated with supergene alteration of porphyry copper deposits is 46.5, 39.5, 25.4, 16–19, and

8.4 Ma (Cook, 1993; McLemore, 1996; S. S. Cook, personal communication, October 1994). The latter period suggests at least five supergene events.

APPENDIX (Caledon)

1950–2006 IM Production data (partial data, draft) for New Mexico. See attached files.

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Appendix to New Mexico paper—Tables of Mineral Commodity Production

MINERALS OVERVIEW

Table 1. Estimated New Mexico industrial-mineral production 2000 to 2009 converted to metric tons for consistency (unless otherwise noted).

Industrial Mineral	Units[3,4]	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000
Adobe	‘000 brick						W	W	W		
	$										
Barite	10^3 mt										
	10^3 $										
Carbon dioxide	10^6 cu ft.										
	10^3 $										
Cement	10^3 mt						W	W	W	W	W
	10^3 $										
Clay	10^3 mt						34	36	33	35	34
(kaolin, fire clay[5])	10^3 $						177	209	175	205	256
Diatomite	mt										
	$										
Feldspar	lt										
	$										
Fluorspar	10^3 mt										
	10^3 $										
Garnet	mt										
	$										
Gemstones[1]	mt						W	W	W	W	W
	10^3 $						20	20	19	33	27
Gypsum	10^3 mt						W	W	W	W	W
(and anhydrite)	10^3 $										
Helium	10^6 cu ft.						W	W	W	W	W
	10^3 $										
Humate	10^3 mt					27	19	16	23	18	10
(“peat”)	10^3 $					2,437	2,254	1,246	2,189	1,631	565

Industrial Mineral	Units[3,4]	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000
Iron minerals	mt $										
Lime	10^3 mt 10^3 $						W	W	W	W	W
Magnesium	mt $										
Manganiferous ore **(5% to 35%)**	10^3 mt 10^3 $										
Manganese conc. **(35% or more)**	10^3 mt 10^3 $										
Mica **(sheet)**	mt $										
Mica **(scrap)**	mt $						W	W	W	W	W
Pegmatite minerals[2]	mt $										
Perlite	10^6 mt 10^6 $						W	W	W	W	W
Potash **K^{2}O equivalent**	10^3 mt 10^6 $					897 283	970 238	966 202	920 189	894 192	1,378 216
Pumice **(pumicite)**	10^3 mt 10^3 $						W	W	W	W	W
Rare earth minerals	mt $										
Salt, common **(halite)**	10^3 mt 10^3 $						W	W	W	W	W
Sand & gravel	10^6 mt 10^6 $						14 90	13 65	13 63	11 55	13 67
Scoria **(volcanic cinders)**	10^3 mt 10^3 $					441 7,630	475 7,853	323 5,659	424 5,736	456 6,009	304 4,873
Sillimanite minerals	mt $										

Industrial Mineral	Units^{3,4}	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000
Silica	mt									W	
(silica sand)	$										
Stone (carvable)	mt										
	$										
Stone (crushed)	10^3 mt						3,430	3,730	3,680	4,230	3,690
	10^6 $						24	26	23	26	22
Stone (dimension)	10^3 mt						57	57	20	36	W
	10^3 $						2,430	2,590	1,370	1,320	W
Stone (decorative)	mt										
	$										
Stone (undifferentiated)	mt										
	$										
Sulfur	mt						W	W	W	W	W
(all forms)	$										
Zeolite	10^3 mt				29	28	21	15	14	14	15
(clinoptilolite)	$				W	W	W	W	W	W	W
Withheld	'000 $										
Total	'000 $										
IM Total Value	'000 $										

1 Reported as gemstones by USBM/USGS but are actually semi-precious stones often omitted from industrial mineral classifications. *106 *

2 Includes beryl (Be), lepidolite (Li), and spodumene (Li); feldspar listed separately because not all is from pegmatites.

3 Units of the original data as reported.

4 Data converted as follows: mt = st/1.1023113; mt = 0.90718474*st

5 Commodity produced but data are not available (W) or data may be withheld by USGS/USBM or not reported. Data are withheld to assure confidentiality when producers are few.

Table 2. Estimated New Mexico industrial-mineral production 1990 to 1999 converted to metric tons for consistency (unless otherwise noted).

Industrial Mineral	Units[3,4]	1999	1998	1997	1996	1995	1994	1993	1992	1991	1990
Adobe	‘000 brick										
	$										
Barite	10^3 mt										
	10^3 $										
Carbon dioxide	10^6 cu ft.										
	10^3 $										
Cement	10^3 mt		W	W	W	W	W	W	W	W	W
	10^3 $		W	W	W	W	W	W	W	W	W
Clay	10^3 mt	W	33	41	32	127			33	28	28
(kaolin, fire clay[5])	10^3 $	W	173	129	165	274			79	74	74
Diatomite	mt										
	$										
Feldspar	lt										
	$										
Fluorspar	10^3 mt										
	10^3 $										
Garnet	mt										
	$										
Gemstones[1]	mt	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	10^3 $	13	W	W	54	22	14	10	34	100	225
Gypsum	10^3 mt		W	W	W	W	W	W	W	W	W
(and anhydrite)	10^3 $		W	W	W	W	W	W	W	W	W
Helium	10^6 cu ft.									W	W
	10^3 $									W	W
Humate	mt										
(“peat”)	$										
Iron minerals	mt										
	$										

Industrial Mineral	Units[3,4]	1999	1998	1997	1996	1995	1994	1993	1992	1991	1990
Lime	10^3 mt 10^3 $										
Magnesium	mt $										
Manganese conc. **(35% or more)**	10^3 mt 10^3 $										
Manganiferous ore **(5% to 35%)**	10^3 mt 10^3 $										
Mica **(scrap)**	mt $								W W	W W	W W
Pegmatite minerals[2]	mt $										
Perlite	10^6 mt 10^6 $	W W	W W	W W	W W	W W	W W	W W	W W	W W	501 13
Potash **K^2O equivalent**	10^3 mt 10^6 $	1,217 235	1,207 231	2,450 240	2,430 225	2,330 209			1,436 257	1,469 251	1,451 246
Pumice **(pumicite)**	10^3 mt 10^3 $		W W	W W	102 527			W W	W W	W W	W W
Rare earth minerals	mt $			NA NA							
Salt, common **(halite)**	10^3 mt 10^3 $		W W	W W	W W	W W	W W	W W	W W	W W	W W
Sand & gravel	10^6 mt 10^6 $	11 53	11 53	9 47	10 49	10 51			10 46	8 36	9 40
Scoria **(volcanic cinders)**	10^3 mt 10^3 $	272 4,028	328 3,341								
Sillimanite minerals	mt $										
Silica **(silica sand)**	mt $										
Stone (carvable)	mt $										

Industrial Mineral	**Units**[3,4]	**1999**	**1998**	**1997**	**1996**	**1995**	**1994**	**1993**	**1992**	**1991**	**1990**
Stone (crushed)	10^3 mt	3,710	4,940	2,920	3,480	3,660			2,722	2,541	2,177
	10^6 $	22	21	16	19	19			14	13	13
Stone (dimension)	10^3 mt	18	W	W	W	W	W	W	W	W	W
	10^3 $	2,320	W	W	W	W	W	W	W	W	W
Stone (decorative)	mt										
	$										
Sulfur	mt										
(all forms)	$										
Zeolite	mt	14,431	12,787	13,620	13,114	18,847	18,979	12,686	4,359	1,677	
(clinoptilolite)	$										
Withheld	‘000 $										
Total	‘000 $										
IM Total Value	‘000 $										

1 Reported as gemstones by USBM/USGS but are actually semi-precious stones often omitted from industrial mineral classifications. *106 *

2 Includes beryl (Be), lepidolite (Li), and spodumene (Li); feldspar listed separately because not all is from pegmatites.

3 Units of the original data as reported.

4 Data converted as follows: mt = st/1.1023114

5 Commodity produced but are data not available (NA) due to withheld by USGS/USBM or not reported.
Data are withheld to assure confidentiality when producers are few.

Table 3. Estimated New Mexico industrial-mineral production 1980 to 1989 converted to metric tons for consistency (unless otherwise noted).

Industrial Mineral	Units[3,4]	1989	1988P	1987	1986	1985	1984	1983	1982	1981	1980
Adobe	‘000 brick										
	$										
Barite	10^3 mt										W
	10^3 $										W
Beryllium	10^3 mt										
	10^3 $										
Carbon dioxide	10^6 cu ft.								W	W	W
	10^3 $								W	W	W
Cement	10^3 mt	W	W	W	W	W	W	W	W	W	W
	10^3 $	W	W	W	W	W	W	W	W	W	W
Clay	10^3 mt	31	29	46	54	54	61	45	54	58	54
(kaolin, fire clay[5])	10^3 $	94	83	141	170	161	143	115	112	119	114
Diatomite	mt										
	$										
Feldspar	lt										
	$										
Fluorspar	mt										
	$										
Garnet	mt										
	$										
Gemstones[1]	mt	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	10^3 $	279	200	200	200	200	200	200	200	200	150
Gypsum	10^3 mt	W	W	W	W	318	288	153	180	151	165
(and anhydrite)	10^3 $	W	W	W	W	1,570	1,622	1,016	887	2,256	1,688
Helium	10^6 cu ft.	W	W	W	W	W	W	W	W	W	W
	10^3 $	W	W	W	W	W	W	W	W	W	W
Humate	mt										1814
(“peat”)	$										40

Industrial Mineral	**Units[3,4]**	**1989**	**1988P**	**1987**	**1986**	**1985**	**1984**	**1983**	**1982**	**1981**	**1980**
Iron minerals	mt $										
Lime	10^3 mt 10^3 $							15 W	W W	W W	W W
Magnesium	mt $										
Manganese conc. **(35% or more)**	10^3 mt 10^3 $										
Manganiferous ore **(5% to 35%)**	10^3 mt 10^3 $									12 W	32 W
Mica **(scrap)**	mt $	W W	W W	W W	W W	W W	W W	W W	W W	W W	W W
Pegmatite minerals[2]	mt $										
Industrial Mineral	Units3,4	1989	1988P	1987	1986	1985	1984	1983	1982	1981	1980
Perlite	10^6 mt 10^6 $	487 13	415 14	396 14	393 14	390 15	377 14	357 13	370 13	444 15	489 14
Potash **K^{2}O equivalent**	10^3 mt 10^6 $	1,365 243	1,271 214	1,323 174	987 133	1,120 156	1,418 204	1,278 175	1,497 205	1,601 261	1,869 289
Pumice **(pumicite)**	10^3 mt 10^3 $	77 795	76 852	79 991	231 2,370	138 1,114	120 1,269	100 1,070	88 809	84 919	76 814
Rare earth minerals	mt $										
Salt, common **(halite)**	10^3 mt 10^3 $	W W	W W	W W	W W	W W	W W	W W	W W	W W	W W
Sand & gravel	10^6 mt 10^6 $	11 45	8 31	8 31	8 26	8 23	8 22	6 20	5 18	6 20	6 18
Scoria **(volcanic cinders)**	mt $										
Sillimanite minerals	mt $										

Industrial Mineral	**Units[3,4]**	**1989**	**1988P**	**1987**	**1986**	**1985**	**1984**	**1983**	**1982**	**1981**	**1980**
Silica **(silica sand)**	mt $										
Stone (carvable)	mt $										
Stone (crushed)	10^3 mt 10^6 $	2,526 12	3,175 14	4,085 16	3,538 15	3,303 15	4,264 17	4,291 15	2,540 14	3,776 12	2,341 9
Stone (dimension)	10^3 mt 10^3 $	W W	20 626	20 626	20 378	18 277	18 185	16 141	16 138	24 173	16 91
Stone (decorative)	mt $										
Sulfur **(all forms)**	mt $										
Zeolite **(clinoptilolite)**	mt $										
Withheld **Total** **IM Total Value**	‘000 $ ‘000 $ ‘000 $										

1 Reported as gemstones by USBM/USGS but are actually semi-precious stones often omitted from industrial mineral classifications. *106 *
2 Includes beryl (Be), lepidolite (Li), and spodumene (Li); feldspar listed separately because not all is from pegmatites.
3 Units of the original data as reported.
4 Data converted as follows: mt = st/1.1023114
5 Commodity produced but are data not available (NA) due to withheld by USGS/USBM or not reported.
Data are withheld to assure confidentiality when producers are few.

Table 4. Estimated New Mexico industrial-mineral production 1970 to 1979 converted to metric tons for consistency (unless otherwise noted).

Industrial Mineral	Units[3,4]	1979	1978P	1977	1976	1975	1974	1973	1972	1971	1970
Adobe	‘000 brick										
	$										
Barite	10^3 mt	W									
	10^3 $	W									
Beryllium	10^3 mt										
	10^3 $										
Carbon dioxide	10^6 cu ft.	W	W	W	857	569	W	W	W	W	W
	10^3 $	W	W	W	80	60	W	W	W	W	W
Cement	10^3 mt	W	W	W	W	W	W	W	W	W	W
	10^3 $	W	W	W	W	W	W	W	W	W	W
Clay	10^3 mt	67	59	63	51	40	50	80	59	69	61
(kaolin, fire clay[5])	10^3 $	124	108	113	116	61	317	169	108	114	91
Diatomite	10^3 mt										
	10^3 $										
Feldspar	lt										
	$										
Fluorspar	mt			W		W	W		W	W	W
	$			W		W	W		W	W	W
Garnet	mt										
	$										
Gemstones[1]	mt	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	10^3 $	180	180	170	210	200	200	70	68	65	60
Gypsum	10^3 mt	228	239	165	W	W	142	231	W	W	W
(and anhydrite)	10^3 $	3,244	2,649	1,227	W	W	532	1,220	W	W	W
Helium	10^6 cu ft.	W	W	W	W	W				W	**?**
	10^3 $	W	W	W	W	W				W	**?**
Humate	mt	1,814	1,814	1,814			3,629	2,722	1,814	907	363
(“peat”)	$	40	60	55			111	50	46	W	7

Industrial Mineral	Units[3,4]	1979	1978P	1977	1976	1975	1974	1973	1972	1971	1970
Iron minerals	mt										
	$										
Lime	10^3 mt	W	W	W	W	W	53	40	25	32	34
	10^3 $	W	W	W	W	W	1,679	793	W	W	W
Magnesium	mt										
	$										
Manganese conc.	10^3 mt										3,833
(35% or more)	10^3 $										W
Manganiferous ore	10^3 mt	30	33	26	41	45	43	29	25	26	42
(5% to 35%)	10^3 $	W	W	W	W	W	W	W	W	W	W
Mica	10^3 mt	15	15	13	W	W	11	9	13	W	W
(scrap)	10^3 $	W	W	W	W	W	60	82	W	W	W
Pegmatite minerals[2]	mt										
	$										
Perlite	10^6 mt	533	523	473	436	389	435	434	432	350	347
	10^6 $	15	13	10	8	6	6	5	6	5	4
Potash	10^3 mt	2,005	1,943	1,891	1,890	1,587	1,907	1,967	2,083	2,078	2,168
K^2O equivalent	10^6 $	229	184	170	165	151	129	92	87	87	86
Pumice	10^3 mt	547	572	415	441	360	427	308	282	260	184
(pumicite)	10^3 $	3,550	2,706	1,835	1,560	1,280	1,466	1,001	809	601	442
Rare earth minerals	mt										
	$										
Salt, common	10^3 mt	W	163	W	W	133	151	W	W	132	W
(halite)	10^3 $	W	1,617	W	W	1,048	W	W	W	1,130	W
Sand & gravel	10^6 mt	6	7	8	7	6	7	10	7	8	10
	10^6 $	18	18	18	17	14	11	16	9	8	11
Scoria	mt										
(volcanic cinders)	$										
Sillimanite minerals	mt										
	$										
Silica	mt										
(silica sand)	$										

Industrial Mineral	Units[3,4]	1979	1978P	1977	1976	1975	1974	1973	1972	1971	1970
Stone (carvable)	mt										
	$										
Stone (crushed)	10^3 mt	2,349	2,212	1,769	1,743		3,203			2,643	2,812
	10^3 $	6,743	6,157	4,786	4,289		8,359			5,337	4,030
Stone (dimension)	10^3 mt	18	16	15	13		W			W	W
	10^3 $	117	115	106	105		W			W	W
Stone (decorative)	mt										
	$										
Stone (undifferentiated)	10^3 mt					1,993		2,567	2,511		
	10^3 $					4,683		5,894	5,499		
Sulfur	mt										
(all forms)	$										
Zeolite	mt										
(clinoptilolite)	$										
Withheld	'000 $										
Total	'000 $										
IM Total Value	'000 $										

1 Reported as gemstones by USBM/USGS but are actually semi-precious stones often omitted from industrial mineral classifications. *106 *

2 Includes beryl (Be), lepidolite (Li), and spodumene (Li); feldspar listed separately because not all is from pegmatites.

3 Units of the original data as reported.

4 Data converted as follows: mt = st/1.1023114

5 Commodity produced but are data not available (NA) due to withheld by USGS/USBM or not reported.
Data are withheld to assure confidentiality when producers are few.

Table 5. Estimated New Mexico industrial-mineral production 1960 to 1969 converted to metric tons for consistency (unless otherwise noted).

Industrial Mineral	Units[3,4]	1969	1968	1967	1966	1965	1964	1963	1962	1961	1960
Adobe	‘000 brick										
	$										
Barite	10^3 mt					181	W	544	229	544	446
	10^3 $					2	W	6	4	10	10
Beryllium	10^3 mt	W	W						31	22	
	10^3 $	W	W						19	12	
Carbon dioxide	10^6 cu ft.	902	749	772	796	834	816	854	827	243	230
	10^3 $	69	52	57	58	62	61	63	74	24	W
Cement	10^3 mt	W	W	W	W	W	W	W	W	W	W
	10^3 $	W	W	W	W	W	W	W	W	W	W
Clay	10^3 mt	64	60	42	W	54	94	W	47	61	51
(kaolin, fire clay[5])	10^3 $	89	89	74	W	101	167	140	156	165	132
Diatomite	10^3 mt										
	10^3 $										
Feldspar	lt	W	98								
	$	W	W								
Fluorspar	10^3 mt	W	W	W			124				
	10^3 $	W	W	W			3				
Garnet	mt										
	$										
Gemstones[1]	mt	NA	NA	NA	NA	NA	NA	W	W	W	W
	10^3 $	60	59	60	45	45	45	45	45	46	40
Gypsum	10^3 mt	128	132	141	132	W	W	162	137	95	50
(and anhydrite)	10^3 $	526	549	588	545	W	W	656	564	386	193
Helium	10^6 cu ft.	**?**	39	71	96	81	82	80	27	42	43
	10^3 $		1,355	2,492	3,357	2,821	2,958	2,787	958	762	684
Humate	mt	363	405								
(“peat”)	$	7	4								

Industrial Mineral	Units[3,4]	1969	1968	1967	1966	1965	1964	1963	1962	1961	1960
Iron minerals	mt										
	$										
Lime	10^3 mt	34	24	15	31	30	23	24	26	23	33
	10^3 $	W	377	243	472	465	352	377	403	350	496
Magnesium	mt										
	$										
Manganese conc.	mt	4,404	6,104	W	W	5,114	5,256	4,864	W		
(35% or more)	10^3 $	131	W	W	W	156	149	137	W		
Manganiferous ore	10^3 mt	45	46	45	43	45	42	37	W	W	W
(5% to 35%)	10^3 $	340	379	348	324	328	300	W	W	W	W
Mica	mt	W	W	W	W	3,867	6,280	W	5,199	1,633	213
(scrap)	10^3 $	W	W	W	W	45	105	W	140	52	7
Mica	lbs							W	W		W
(sheet)	10^3 $							W	W		W
Pegmatite minerals[2]	mt										
	$										
Perlite	10^6 mt	361	332	314	311	300	260	235	234	223	218
	10^3 $	4,493	3,706	3,424	3,423	2,905	2,568	2,212	2,143	2,159	2,119
Potash	10^3 mt	2,111	2,077	2,615	2,679	2,584	2,427	2,398	2,003	2,289	2,214
K^2O equivalent	10^6 $	62	63	91	109	118	105	101	85	96	83
Pumice	10^3 mt	205	220	200	222	239	236	292	279	308	331
(pumicite)	10^3 $	415	527	639	787	915	760	850	741	879	827
Rare earth minerals	mt										
	$										
Salt, common	10^3 mt	W	W	74	60	58	56	49	39	30	35
(halite)	10^3 $	W	W	1,036	716	572	559	472	334	284	331
Sand & gravel	10^6 mt	8	11	13	14	11	8	7	6	11	7
	10^6 $	10	12	14	13	12	10	13	8	10	7
Scoria	mt										
(volcanic cinders)	$										
Sillimanite minerals	mt										
	$										

Industrial Mineral	Units[3,4]	1969	1968	1967	1966	1965	1964	1963	1962	1961	1960
Silica **(silica sand)**	mt $										
Stone (carvable)	mt $										
Stone (crushed)	10^{3} mt 10^{6} $										
Stone (dimension)	10^{3} mt 10^{3} $										
Stone (decorative)	mt $										
Stone (undifferentiated)	10^{3} mt 10^{3} $	2,564 3,286	2,019 3,527	1,262 2,403	2,406 4,056	1,734 3,020	2,504 4,244	2,276 4,236	1,818 2,782	1,681 2,206	1,158 1,692
Sulfur **(all forms)**	mt $										
Zeolite **(clinoptilolite)**	mt $										
Withheld **Total** **IM Total Value**	‘000 $ ‘000 $ ‘000 $										

1 Reported as gemstones by USBM/USGS but are actually semi-precious stones often omitted from industrial mineral classifications. *106 *

2 Includes beryl (Be), lepidolite (Li), and spodumene (Li); feldspar listed separately because not all is from pegmatites.

3 Units of the original data as reported.

4 Data converted as follows: mt = st/1.1023114

5 Commodity produced but are data not available (NA) due to withheld by USGS/USBM or not reported.
Data are withheld to assure confidentiality when producers are few.

Table 6. Estimated New Mexico industrial-mineral production 1950 to 1959 converted to metric tons for consistency (unless otherwise noted).

Industrial Mineral	Units[3,4]	1959	1958	1957	1956	1955	1954	1953	1952	1951	1950
Adobe	‘000 brick										
	$										
Barite	10^3 mt	290	W	4,029	3,682	W	W	W	W	W	W
	10^3 $	6	W	98	81	W	W	W	W	W	W
Beryllium	10^3 mt	10	24	26	28	96	106	81	92	128	W
	10^3 $	6	16	15	W	56	44	52	29	47	W
Carbon dioxide	10^6 cu ft.	W	W	W	W	W	W	W	W	W	68
	10^3 $	W	W	W	W	W	W	W	W	W	27
Cement	10^3 mt	W									
	10^3 $	W									
Clay	10^3 mt	41	36	30	36	41	43	45	52	69	57
(kaolin, fire clay[5])	10^3 $	77	73	83	95	109	83	104	149	149	78
Diatomite	10^3 mt					W	W	W			
	10^3 $					W	W	W			
Feldspar	lt										
	10^3 $										
Fluorspar	10^3 mt	181				W	8	10	15	22	18
	10^3 $	7				W	W	W	823	1,163	742
Garnet	mt										
	$										
Gemstones[1]	mt	W	W	W	W	W	W	W	W	W	W
	10^3 $	39	28	30	30	25	W	W	W	W	W
Gypsum	mt						805				
(and anhydrite)	$						2,661				
Helium	10^6 cu ft.	17	30	69	76	54	42	11			
	10^3 $	264	502	1,189	1,350	946	735	150			
Humate	mt										
(“peat”)	$										

Industrial Mineral	**Units[3,4]**	**1959**	**1958**	**1957**	**1956**	**1955**	**1954**	**1953**	**1952**	**1951**	**1950**
Iron minerals	mt									29,220	13
	$									NA	NA
Lime	10^3 mt	15	19	22	28						
	10^3 $	209	260	290	373						
Magnesium	mt										
	$										
Manganese conc.	10^3 mt	25	26	23	20	1			2	0.2	1
(35% or more)	10^3 $	2,248	2,333	2,114	1,835	W			157	W	W
Manganiferous ore	10^3 mt		W	39	35	37	19	W	48	72	67
(5% to 35%)	10^3 $		W	152	139	W	82	W	W	W	W
Mica	mt	191	714	1,222	696	76					
(scrap)	10^3 $	7	24	47	22	2					
Mica	lbs	247	1,791	2,134	6,247	9,431	2,054				W
(sheet)	10^3 $	2	18	16	53	65	14				W
Pegmatite minerals[2]	mt										
	$										
Perlite	10^6 mt	218	183	170	152	134	101	77	W	W	W
	10^3 $	2,121	1,790	1,568	1,271	1,091	886	662	W	W	W
Potash	10^3 mt	1,986	1,794	1,887	1,812	1,670	1,571	1,409	1,280	1,105	973
K^2O equivalent	10^6 $	74	69	77	75	70	64	58	46	37	32
Pumice	10^3 mt	447	460	291	265	357	330	480	197	223	319
(pumicite)	10^3 $	1,023	959	756	667	780	1,060	760	755	884	1,110
Rare earth minerals	mt										
	$										
Salt, common	10^3 mt	33	28	48	52	45	46	56	W	W	W
(halite)	10^3 $	322	275	429	501	597	333	216	W	W	W
Sand & gravel	10^3 mt	11,304	11,979	7,249	5,493	4,134	5,914	1,285	451	980	851
	10^3 $	13,332	11,413	7,803	5,776	6,005	8,341	1,239	500	1,088	923
Scoria	mt										
(volcanic cinders)	$										
Sillimanite minerals	mt										
	$										

Industrial Mineral	Units[3,4]	1959	1958	1957	1956	1955	1954	1953	1952	1951	1950
Silica	mt										
(silica sand)	$										
Stone (carvable)	mt										
	$										
Stone (crushed)	10^3 mt										
	10^6 $										
Stone (dimension)	10^3 mt										
	10^3 $										
Stone (decorative)	mt										
	$										
Stone (undifferentiated)	10^3 mt	418	1,569	1,223	1,150	1,427	700	567	288	928	331
	10^3 $	542	1,507	1,618	1,272	1,547	714	511	192	592	244
Sulfur	mt				W	W	W	W			
(all forms)	$				W	W	W	W			
Zeolite	mt										
(clinoptilolite)	$										
Withheld	‘000 $										
Total	‘000 $										
IM Total Value	‘000 $										

1 Reported as gemstones by USBM/USGS but are actually semi-precious stones often omitted from industrial mineral classifications. *106 *
2 Includes beryl (Be), lepidolite (Li), and spodumene (Li); feldspar listed separately because not all is from pegmatites.
3 Units of the original data as reported.
4 Data converted as follows: mt = st/1.1023114
5 Commodity produced but are data not available (NA) due to withheld by USGS/USBM or not reported.

INDIVIDUAL MINERALS

Table 1. **Adobe** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Adobe Year	10^3 mt	10^3 st	10^3 \$	Sources	Remarks
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4	W	W	W	USGS	
3	W	W	W	USGS	
2	W	W	W	USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	

Adobe Year	10^3 mt	10^3 st	10^3 $	Sources	Remarks
71				BOM	
1970				BOM	
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 2. **Barite** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Barite **Year**	**10^3 mt**	**10^3 st**	**10^3 \$**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980	**W**	**W**	**W**	BOM	
79	**W**	**W**	**W**	BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	
71				BOM	

Barite **Year**	**10^3 mt**	**10^3 st**	**10^3 \$**	**Sources**	**Remarks**
1970				BOM	
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65	*181*	**200**	2	BOM	
64	*W*	**W**	W	BOM	
63	*544*	**600**	6	BOM	
62	*229*	**252**	4	BOM	
61	*544*	**600**	10	BOM	
1960	*446*	**492**	10	BOM	
59	*290*	**320**	6	BOM	
58		**W**	W	BOM	
57	*4,029*	**4,441**	98	BOM	
56	*3,682*	**4,059**	81	BOM	
55	*W*	**W**	W	BOM	
54	*W*	**W**	W	BOM	
53	*W*	**W**	W	BOM	
52	*W*	**W**	W	BOM	
51	*W*	**W**	W	BOM	
1950	*W*	**W**	W	BOM	
Total					

Table 3. **Beryllium** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Berryllium Year	mt	st	10^3 $	Sources	Remarks
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	
71				BOM	
1970				BOM	

Berryllium **Year**	**mt**	**st**	**$10^3 \$$**	**Sources**	**Remarks**
69	*W*	**W**	W	BOM	
68	*W*	**W**	W	BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62	*31*	**34**	19	BOM	
61	*22*	**24**	12	BOM	
1960				BOM	
59	*10*	**11**	6	BOM	
58	*24*	**27**	16	BOM	
57	*26*	**29**	15	BOM	
56	*28*	**31**	W	BOM	
***55**	*96*	**106**	56,420	BOM	
***54**	*106*	**117**	43,771	BOM	
***53**	*81*	**89**	52,014	BOM	
***52**	*92*	**101**	29,185	BOM	
***51**	*128*	**141**	47,008	BOM	
1950	*W*	**W**	W	BOM	
Total					

* $ not in thousands

Table 4. **Carbon dioxide** production by year in metric cubic feet (MCF), and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Carbon Dioxide Year	10^3 MCF	10^3 $	Sources	Remarks
2010			USGS	
9			USGS	
8			USGS	
7			USGS	
6			USGS	
5			USGS	
4			USGS	
3			USGS	
2			USGS	
1			USGS	
2000			USGS	
99			USGS	
98			USGS	
97			USGS	
96			USGS	
95			USGS	
94			BOM	
93			BOM	
92			BOM	
91			BOM	
1990			BOM	
89			BOM	
88			BOM	
87			BOM	
86			BOM	
85			BOM	
84			BOM	
83			BOM	
82	**W**	W	BOM	
81	**W**	W	BOM	
1980	**W**	W	BOM	
79	**W**	W	BOM	
78	**W**	W	BOM	
77	**W**	W	BOM	
76	**856,548**	80	BOM	
75	**569,352**	60	BOM	
74	**W**	W	BOM	
73	**W**	W	BOM	
72	**W**	W	BOM	

Carbon Dioxide **Year**	**10^3 MCF**	**10^3 $**	**Sources**	**Remarks**
71	**W**	W	BOM	
1970	**W**	W	BOM	
69	**902,186**	69	BOM	
68	**749,364**	52	BOM	
67	**771,516**	57	BOM	
66	**795,885**	58	BOM	
65	**833,819**	62	BOM	
64	**816,168**	61	BOM	
63	**854,339**	63	BOM	
62	**826,810**	74	BOM	
61	**242,903**	24	BOM	
1960	**230,115**	W	BOM	
59	**W**	W	BOM	
58	**W**	W	BOM	
57	**W**	W	BOM	
56	**W**	W	BOM	
55	**W**	W	BOM	
54	**W**	W	BOM	
53	**W**	W	BOM	
52	**W**	W	BOM	
51	**W**	W	BOM	
1950	**68,000**	27	BOM	
Total				

Table 5. **Cement** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Cement Year	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4	*W*	*W*	*W*	USGS	
3	*W*	*W*	*W*	USGS	
2	*W*	*W*	*W*	USGS	
1	*W*	*W*	*W*	USGS	
2000	*W*	*W*	*W*	USGS	
99	*W*	*W*	*W*	USGS	
98	*W*	**W**	W	USGS	
97	*W*	**W**	W	USGS	
96	*W*	**W**	W	USGS	
95	*W*	**W**	W	USGS	
94	*W*	**W**	W	BOM	
93	*W*	**W**	W	BOM	
92	*W*	**W**	W	BOM	
91	*W*	**W**	W	BOM	
1990	*W*	**W**	W	BOM	
89	*W*	**W**	W	BOM	
88	*W*	**W**	W	BOM	
87	*W*	**W**	W	BOM	
86	*W*	**W**	W	BOM	
85	*W*	**W**	W	BOM	
84	*W*	**W**	W	BOM	
83	*W*	**W**	W	BOM	
82	*W*	**W**	W	BOM	
81	*W*	**W**	W	BOM	
1980	*W*	**W**	W	BOM	
79	*W*	**W**	W	BOM	
78	*W*	**W**	W	BOM	
77	*W*	**W**	W	BOM	
76	*W*	**W**	W	BOM	
75	*W*	**W**	W	BOM	
74	*W*	**W**	W	BOM	
73	*W*	**W**	W	BOM	
72	*W*	**W**	W	BOM	
71	*W*	**W**	W	BOM	

Cement Year	**10^3 mt**	**10^3 st**	**10^3 \$**	**Sources**	**Remarks**
1970	*W*	**W**	W	BOM	
69	*W*	**W**	W	BOM	
68	*W*	**W**	W	BOM	
67	*W*	**W**	W	BOM	
66	*W*	**W**	W	BOM	
65	*W*	**W**	W	BOM	
64	*W*	**W**	W	BOM	
63	*W*	**W**	W	BOM	
62	*W*	**W**	W	BOM	
61	*W*	**W**	W	BOM	
1960	*W*	**W**	W	BOM	
59	*W*	**W**	W	BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 6. **Clay** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Clay Year	10^3 mt	10^3 st	10^3 $	Sources	Remarks
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4	**34**	*31*	177	USGS	
3	**36**	*33*	209	USGS	
2	**33**	*36*	175	USGS	
1	**35**	*39*	205	USGS	
2000	**34**	*37*	256	USGS	
99	**W**	*W*	W	USGS	
98	**33**	*36*	173	USGS	
97	**41**	*45*	129	USGS	
96	**32**	*35*	165	USGS	
95	**127**	*140*	274	USGS	
94				BOM	
93				BOM	
*92	**32,645**	*35,985*	79	BOM	
*91	**27,794**	*30,638*	74	BOM	
*1990	**27,994**	*30,858*	74	BOM	
*89	**31,012**	*34,185*	94	BOM	
*88	**28,555**	*31,477*	83	BOM	
*87	*46,491*	**51,248**	141	BOM	
86	*54*	**60**	170	BOM	
85	*54*	**60**	161	BOM	
84	*61*	**67**	143	BOM	
83	*45*	**50**	115	BOM	
82	*54*	**60**	112	BOM	
81	*58*	**64**	119	BOM	
1980	*54*	**60**	114	BOM	
79	*67*	**74**	124	BOM	
78	*59*	**65**	108	BOM	
77	*63*	**69**	113	BOM	
76	*51*	**56**	116	BOM	
75	*40*	**44**	61	BOM	
74	*50*	**55**	317	BOM	
73	*80*	**88**	169	BOM	
72	*59*	**65**	108	BOM	
71	*69*	**76**	114	BOM	

Clay **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
1970	*61*	**67**	91	BOM	
69	*64*	**70**	89	BOM	
68	*60*	**66**	89	BOM	
67	*42*	**46**	74	BOM	
66	*W*	**W**	W	BOM	
65	*54*	**60**	101	BOM	
64	*94*	**104**	167	BOM	
63	*W*	**W**	140	BOM	
62	*47*	**52**	156	BOM	
61	*61*	**67**	165	BOM	
1960	*51*	**56**	132	BOM	
59	*41*	**45**	77	BOM	
58	*36*	**40**	73	BOM	
57	*30*	**33**	83	BOM	
56	*36*	**40**	95	BOM	
****55**	*41,142*	**45,351**	108,582	BOM	
****54**	*43,392*	**47,832**	83,085	BOM	
****53**	*44,533*	**49,089**	103,931	BOM	
****52**	*52,316*	**57,668**	107,633	BOM	
****51**	*68,631*	**75,653**	148,876	BOM	
1950	*57*	**63**	78	BOM	
Total					

* mt and st not in thousands

** values not in thousands

Table 7. **Diatomite** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Diatomite **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	

Diatomite Year	10^3 mt	10^3 st	10^3 $	Sources	Remarks
71				BOM	
1970				BOM	
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55	*W*	**W**	W	BOM	
54	*W*	**W**	W	BOM	
53	*W*	**W**	W	BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 8. **Feldspar** production by year in long tons (lt) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Feldspar Year	lt	10^3 $	Sources	Remarks
2010			USGS	
9			USGS	
8			USGS	
7			USGS	
6			USGS	
5			USGS	
4			USGS	
3			USGS	
2			USGS	
1			USGS	
2000			USGS	
99			USGS	
98			USGS	
97			USGS	
96			USGS	
95			USGS	
94			BOM	
93			BOM	
92			BOM	
91			BOM	
1990			BOM	
89			BOM	
88			BOM	
87			BOM	
86			BOM	
85			BOM	
84			BOM	
83			BOM	
82			BOM	
81			BOM	
1980			BOM	
79			BOM	
78			BOM	
77			BOM	
76			BOM	
75			BOM	
74			BOM	
73			BOM	
72			BOM	
71			BOM	

Feldspar Year	lt	10^3 $	Sources	Remarks
1970			BOM	
69	W	W	BOM	
68	98	W	BOM	
67			BOM	
66			BOM	
65			BOM	
64			BOM	
63			BOM	
62			BOM	
61			BOM	
1960			BOM	
59			BOM	
58			BOM	
57			BOM	
56			BOM	
55			BOM	
54			BOM	
53			BOM	
52			BOM	
51			BOM	
1950			BOM	
Total				

Table 9. **Fluorospar** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Fluorospar **Year**	**mt**	**st**	**$**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77	*W*	**W**	W	BOM	
76				BOM	
75	*W*	**W**	W	BOM	
74	*W*	**W**	W	BOM	
73				BOM	
72	*W*	**W**	W	BOM	
71	*W*	**W**	W	BOM	

Fluorospar **Year**	**mt**	**st**	**$**	**Sources**	**Remarks**
1970	*W*	**W**	W	BOM	
69	*W*	**W**	W	BOM	
68	*W*	**W**	W	BOM	
67	*W*	**W**	W	BOM	
66				BOM	
65				BOM	
64	*124,284*	**137,000**	3,000	BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59	*181,437*	**200,000**	7,000	BOM	
58				BOM	
57				BOM	
56				BOM	
55	*W*	**W**	W	BOM	
54	*8,052*	**8,876**	W	BOM	
53	*10,786*	**11,890**	W	BOM	
52	*14,917*	**16,443**	823,320	BOM	
51	*22,137*	**24,402**	1,163,098	BOM	
1950	*18,176*	**20,036**	742,000	BOM	
Total					

Table 10. **Garnet** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Garnet Year	10^3 mt	10^3 st	10^3 $	Sources	Remarks
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	
71				BOM	
1970				BOM	

Garnet Year	10^3 mt	10^3 st	10^3 $	Sources	Remarks
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 11. **Gemstones** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Gemstones **Year**	**10^3 mt**	**10^3 st**	**10^3 \$**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4	W	**W**	20	USGS	
3	W	**W**	20	USGS	
2	W	**W**	19	USGS	
1	W	**W**	33	USGS	
2000	W	**W**	27	USGS	
99	W	**W**	13	USGS	
98	W	**W**	11	USGS	
97	W	**W**	54	USGS	
96	W	**W**	54	USGS	
95	W	**W**	22	USGS	
94				BOM	
93				BOM	
92	W	**W**	34	BOM	
91	W	**W**	100	BOM	
1990	W	**W**	225	BOM	
89	W	**W**	279	BOM	
88	W	**W**	200	BOM	
87	W	**W**	200	BOM	
86	W	**W**	200	BOM	
85	W	**W**	200	BOM	
84	W	**W**	200	BOM	
83	W	**W**	200	BOM	
82	W	**W**	200	BOM	
81	W	**W**	200	BOM	
1980	W	**W**	150	BOM	
79	W	**W**	180	BOM	
78	W	**W**	180	BOM	
77	W	**W**	170	BOM	
76	W	**W**	210	BOM	
75	W	**W**	200	BOM	
74	W	**W**	200	BOM	
73	W	**W**	70	BOM	
72	W	**W**	68	BOM	
71	W	**W**	65	BOM	
1970	W	**W**	60	BOM	

Gemstones Year	10^3 mt	10^3 st	10^3 $	Sources	Remarks
69	W	**W**	60	BOM	
68	W	**W**	59	BOM	
67	W	**W**	60	BOM	
66	W	**W**	45	BOM	
65	W	**W**	45	BOM	
64	W	**W**	45	BOM	
63	W	**W**	45	BOM	
62	W	**W**	45	BOM	
61	W	**W**	46	BOM	
1960	W	**W**	40	BOM	
59	W	**W**	39	BOM	
58	W	**W**	28	BOM	
57	W	**W**	30	BOM	
56	W	**W**	30	BOM	
55	W	**W**	25	BOM	
54	W	**W**	W	BOM	
53	W	**W**	W	BOM	
52	W	**W**	W	BOM	
51	W	**W**	W	BOM	
1950	W	**W**	W	BOM	
Total					

Table 12. **Gypsum** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Gypsum Year	10^3 mt	10^3 st	10^3 $	Sources	Remarks
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4	*W*	**W**	W	USGS	
3	*W*	**W**	W	USGS	
2	*W*	**W**	W	USGS	
1	*W*	**W**	W	USGS	
2000	*W*	**W**	W	USGS	
99	*W*	**W**	W	USGS	
98	*W*	**W**	W	USGS	
97	*W*	**W**	W	USGS	
96	*W*	**W**	W	USGS	
95	*W*	**W**	W	USGS	
94	*W*	**W**	W	BOM	
93	*W*	**W**	W	BOM	
92	*W*	**W**	W	BOM	
91	*W*	**W**	W	BOM	
1990	*W*	**W**	W	BOM	
89	*W*	**W**	W	BOM	
88	*W*	**W**	W	BOM	
87	*W*	**W**	W	BOM	
86	*W*	**W**	W	BOM	
85	*318*	**350**	1,570	BOM	
84	*288*	**318**	1,622	BOM	
83	*153*	**169**	1,016	BOM	
82	*180*	**198**	887	BOM	
81	*151*	**166**	2,256	BOM	
1980	*165*	**182**	1,688	BOM	
79	*228*	**251**	3,244	BOM	
78	*239*	**263**	2,649	BOM	
77	*165*	**182**	1,227	BOM	
76	*W*	**W**	W	BOM	
75	*W*	**W**	W	BOM	
74	*142*	**157**	532	BOM	
73	*231*	**255**	1,220	BOM	
72	*W*	**W**	W	BOM	
71	*W*	**W**	W	BOM	

Gypsum **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
1970	*W*	**W**	W	BOM	
69	*128*	**141**	526	BOM	
68	*132*	**146**	549	BOM	
67	*141*	**155**	588	BOM	
66	*132*	**146**	545	BOM	
65	*W*	**W**	W	BOM	
64	*W*	**W**	W	BOM	
63	*162*	**179**	656	BOM	
62	*137*	**151**	564	BOM	
61	*95*	**105**	386	BOM	
1960	*50*	**55**	193	BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54*	*805*	**887**	2,661	BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

* Values not in thousands

Table 13. **Helium** production by year in cubic feet (CF) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Helium **Year**	**10^3 CF**	**10^3 $**	**Sources**	**Remarks**
2010			USGS	
9			USGS	
8			USGS	
7			USGS	
6			USGS	
5			USGS	
4	**W**	W	USGS	
3	**W**	W	USGS	
2	**W**	W	USGS	
1	**W**	W	USGS	
2000	**W**	W	USGS	
99			USGS	
98			USGS	
97			USGS	
96			USGS	
95			USGS	
94			BOM	
93			BOM	
92			BOM	
91	**W**	W	BOM	
1990	**W**	W	BOM	
89	**W**	W	BOM	
88	**W**	W	BOM	
87	**W**	W	BOM	
86	**W**	W	BOM	
85	**W**	W	BOM	
84	**W**	W	BOM	
83	**W**	W	BOM	
82	**W**	W	BOM	
81	**W**	W	BOM	
1980	**W**	W	BOM	
79			BOM	
78	**W**	W	BOM	
77	**W**	W	BOM	
76	**W**	W	BOM	
75	**W**	W	BOM	
74			BOM	
73			BOM	
72	**W**	W	BOM	

Helium **Year**	**10^3 CF**	**10^3 $**	**Sources**	**Remarks**
71	**W**	W	BOM	
1970	**?**	?	BOM	
69	**?**	?	BOM	
68	**39,100**	1,355	BOM	
67	**71,200**	2,492	BOM	
66	**95,900**	3,357	BOM	
65	**80,583**	2,821	BOM	
64	**82,105**	2,958	BOM	
63	**79,624**	2,787	BOM	
62	**27,377**	958	BOM	
61	**42,224**	762	BOM	
1960	**43,494**	684	BOM	
59	**16,903**	264	BOM	
58	**29,793**	502	BOM	
57	**69,336**	1,189	BOM	
56	**76,072**	1,350	BOM	
55	**53,721**	946,447	BOM	
54*	**41,754,600**	735,183	BOM	
53*	**11,158,000**	150,127	BOM	
52			BOM	
51			BOM	
1950			BOM	
Total				

* Value not in thousands

** $ not in thousands

Table 14. **Humate** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Humate Year	**mt**	**st**	**$10^3\ \$$**	**Sources**	**Remarks**
2010					
9					
8					
7					
6					
5	*27,032*	**29,797**	**2,437**	EMNRD-MMD	
4	*18,643*	**20,550**	**2,254**	EMNRD-MMD	
3	*15,641*	**17,241**	**1,246**	EMNRD-MMD	
2	*22,781*	**25,111**	**2,189**	EMNRD-MMD	
1	*17,532*	**19,325**	**1,631**	EMNRD-MMD	
2000	*10,251*	**11,300**	**565**	EMNRD-MMD	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980	*1,814*	**2,000**	40	BOM	
79	*1,814*	**2,000**	40	BOM	
78	*1,814*	**2,000**	60	BOM	
77	*1,814*	**2,000**	55	BOM	
76				BOM	
75				BOM	
74	*3,629*	**4,000**	111	BOM	
73	*2,722*	**3,000**	50	BOM	
72	*1,814*	**2,000**	46	BOM	
71	*907*	**1,000**	W	BOM	
1970	*363*	**400**	7	BOM	

Humate **Year**	**mt**	**st**	**10^3 $**	**Sources**	**Remarks**
69	*363*	**400**	4	BOM	
68	*405*	**446**	4	BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 15. **Iron minerals** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Iron Minerals Year	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	

Iron Minerals Year	10^3 mt	10^3 st	10^3 \$	Sources	Remarks
71				BOM	
1970				BOM	
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 16. **Lime** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Lime Year	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4	**W**	**W**	**W**	USGS	
3	**W**	**W**	**W**	USGS	
2	**W**	**W**	**W**	USGS	
1	**W**	**W**	**W**	USGS	
2000	**W**	**W**	**W**	USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83	*15*	**17**	W	BOM	
82	*W*	**W**	W	BOM	
81	*W*	**W**	W	BOM	
1980	*W*	**W**	W	BOM	
79	*W*	**W**	W	BOM	
78	*W*	**W**	W	BOM	
77	*W*	**W**	W	BOM	
76	*W*	**W**	W	BOM	
75	*W*	**W**	W	BOM	
74	*53*	**58**	1,679	BOM	
73	*40*	**44**	793	BOM	
72	*25*	**28**	W	BOM	
71	*32*	**35**	W	BOM	

Lime					
Year	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
1970	*34*	**37**	W	BOM	
69	*34*	**37**	W	BOM	
68	*24*	**27**	377	BOM	
67	*15*	**17**	243	BOM	
66	*31*	**34**	472	BOM	
65	*30*	**33**	465	BOM	
64	*23*	**25**	352	BOM	
63	*24*	**27**	377	BOM	
62	*26*	**29**	403	BOM	
61	*23*	**25**	350	BOM	
1960	*33*	**36**	496	BOM	
59	*15*	**16**	209	BOM	
58	*19*	**21**	260	BOM	
57	*22*	**24**	290	BOM	
***56**	*27,915*	**30,771**	372,641	BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

* Values not in thousands

Table 17. **Magnesium** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Magnesium **Year**	**10^3 mt**	**10^3 st**	**10^3 \$**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	
71				BOM	
1970				BOM	

Magnesium Year	10^3 mt	10^3 st	10^3 $	Sources	Remarks
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 18. **Magniferous ore (5%-35%)** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Magniferous Ore **Year**	**mt**	**st**	**10^3 $**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81	*11,558*	**12,741**	W	BOM	
1980	*31,931*	**35,198**	W	BOM	
79	*30,075*	**33,152**	W	BOM	
78	*33,061*	**36,443**	W	BOM	
77	*26,417*	**29,120**	W	BOM	
76	*41,152*	**45,362**	W	BOM	
75	*45,337*	**49,976**	W	BOM	
74	*42,953*	**47,348**	W	BOM	
73	*29,106*	**32,084**	W	BOM	
72	*25,253*	**27,837**	W	BOM	

Magniferous Ore Year	mt	st	10^3 $	Sources	Remarks
71	*25,846*	**28,490**	W	BOM	
1970	*41,881*	**46,166**	W	BOM	
69	*44,584*	**49,146**	340	BOM	
68	*45,977*	**50,681**	379	BOM	
67	*44,745*	**49,323**	348	BOM	
66	*43,173*	**47,590**	324	BOM	
65	*45,441*	**50,090**	328	BOM	
64	*42,327*	**46,657**	300	BOM	
63	*37,325*	**41,144**	W	BOM	
62	*W*	**W**	W	BOM	
61	*W*	**W**	W	BOM	
1960	*W*	**W**	W	BOM	
59				BOM	
58	*W*	**W**	W	BOM	
57	*38,587*	**42,535**	152	BOM	
56	*35,182*	**38,782**	139	BOM	
55	*36,578*	**40,320**	W	BOM	
***54**	*18,639*	**20,546**	82,184	BOM	
53	*W*	**W**	W	BOM	
52	*48,021*	**52,934**	W	BOM	
51	*72,433*	**79,844**	W	BOM	
1950	*67,447*	**74,348**	W	BOM	
Total					

* $ not in thousands

Table 19. **Manganese conc (35% or more)** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Manganese conc Year	mt	st	10^3 $	Sources	Remarks
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	

Manganese conc **Year**	**mt**	**st**	**10^3 $**	**Sources**	**Remarks**
71				BOM	
1970	*3,833*	**4,225**	W	BOM	
69	*4,404*	**4,855**	131	BOM	
68	*6,104*	**6,729**	W	BOM	
67	*W*	**W**	W	BOM	
66	*W*	**W**	W	BOM	
65	*5,114*	**5,637**	156	BOM	
64	*5,256*	**5,794**	149	BOM	
63	*4,864*	**5,362**	137	BOM	
62	*W*	**W**	W	BOM	
61				BOM	
1960				BOM	
59	*24,973*	**27,528**	2,248	BOM	
58	*26,187*	**28,866**	2,333	BOM	
57	*23,096*	**25,459**	2,114	BOM	
56	*19,969*	**22,012**	1,835	BOM	
55	*1,261*	**1,390**	W	BOM	
54				BOM	
53				BOM	
***52**	*2,141*	**2,360**	156,745	BOM	
51	*205*	**226**	W	BOM	
1950	*1,197*	**1,320**	W	BOM	
Total					

* $ not in thousands

Table 20. **Mica (sheet)** production by year in pounds (lbs) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Mica (Sheet) Year	lbs	10^3 $	Sources	Remarks
2010			USGS	
9			USGS	
8			USGS	
7			USGS	
6			USGS	
5			USGS	
4			USGS	
3			USGS	
2			USGS	
1			USGS	
2000			USGS	
99			USGS	
98			USGS	
97			USGS	
96			USGS	
95			USGS	
94			BOM	
93			BOM	
92			BOM	
91			BOM	
1990			BOM	
89			BOM	
88			BOM	
87			BOM	
86			BOM	
85			BOM	
84			BOM	
83			BOM	
82			BOM	
81			BOM	
1980			BOM	
79			BOM	
78			BOM	
77			BOM	
76			BOM	
75			BOM	
74			BOM	
73			BOM	
72			BOM	

Mica (Sheet) **Year**	**lbs**	**10^3 $**	**Sources**	**Remarks**
71			BOM	
1970			BOM	
69			BOM	
68			BOM	
67			BOM	
66			BOM	
65			BOM	
64			BOM	
63	**W**	W	BOM	
62	**W**	W	BOM	
61			BOM	
1960	**W**	W	BOM	
59	**247**	2	BOM	
58	**1,791**	18	BOM	
57	**2,134**	16	BOM	
56	**6,247**	53	BOM	
***55**	**9,431**	64,930	BOM	
***54**	**2,054**	13,845	BOM	
53			BOM	
52			BOM	
51			BOM	
1950	**W**	W	BOM	
Total				

* $ not in thousands

Table 21. **Mica (scrap)** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Mica (scrap) Year	mt	st	10^3 $	Sources	Remarks
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4	*W*	**W**	W	USGS	
3	*W*	**W**	W	USGS	
2	*W*	**W**	W	USGS	
1	*W*	**W**	W	USGS	
2000	*W*	**W**	W	USGS	
99				USGS	
98	*W*	**W**	W	USGS	
97	*W*	**W**	W	USGS	
96	*W*	**W**	W	USGS	
95	*W*	**W**	W	USGS	
94	*W*	**W**	W	BOM	
93	*W*	**W**	W	BOM	
92	*W*	**W**	W	BOM	
91	*W*	**W**	W	BOM	
1990	*W*	**W**	W	BOM	
89	*W*	**W**	W	BOM	
88	*W*	**W**	W	BOM	
87	*W*	**W**	W	BOM	
86	*W*	**W**	W	BOM	
85	*W*	**W**	W	BOM	
84	*W*	**W**	W	BOM	
83	*W*	**W**	W	BOM	
82	*W*	**W**	W	BOM	
81	*W*	**W**	W	BOM	
1980	*W*	**W**	W	BOM	
79	*15,422*	**17,000**	W	BOM	
78	*14,515*	**16,000**	W	BOM	
77	*12,701*	**14,000**	W	BOM	
76	*W*	**W**	W	BOM	
75	*W*	**W**	W	BOM	
74	*10,886*	**12,000**	60	BOM	
73	*9,072*	**10,000**	82	BOM	
72	*12,701*	**14,000**	W	BOM	

Mica (scrap) **Year**	**mt**	**st**	**10^3 $**	**Sources**	**Remarks**
71	*W*	**W**	W	BOM	
1970	*W*	**W**	W	BOM	
69	*W*	**W**	W	BOM	
68	*W*	**W**	W	BOM	
67	*W*	**W**	W	BOM	
66	*W*	**W**	W	BOM	
65	*3,867*	**4,263**	45	BOM	
64	*6,280*	**6,922**	105	BOM	
63	*W*	**W**	W	BOM	
62	*5,199*	**5,731**	140	BOM	
61	*1,633*	**1,800**	52	BOM	
1960	*213*	**235**	7	BOM	
59	*191*	**210**	7	BOM	
58	*714*	**787**	24	BOM	
57	*1,222*	**1,347**	47	BOM	
***56**	*696*	**767**	22,213	BOM	
***55**	*76*	**84**	2,475	BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

* $ not in thousands

Table 22. **Pegmatite** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Pegmatite **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	
71				BOM	
1970				BOM	

Pegmatite Year	10^3 mt	10^3 st	10^3 \$	Sources	Remarks
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 23. **Perlite** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Perlite Year	**10^3 mt**	**10^3 st**	**10^3 \$**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4	W	W	W	USGS	
3	W	W	W	USGS	
2	W	W	W	USGS	
1	W	W	W	USGS	
2000	W	W	W	USGS	
99	W	W	W	USGS	
98	W	W	W	USGS	
97	W	W	W	USGS	
96	W	W	W	USGS	
95	W	W	W	USGS	
94				BOM	
93				BOM	
92	**W**	*W*	W	BOM	
91	**W**	*W*	W	BOM	
1990	**501**	*552*	13,181	BOM	
89	**487**	*537*	13,080	BOM	
88	*415*	**458**	14,294	BOM	
87	*396*	**437**	13,611	BOM	
86	*393*	**433**	13,727	BOM	
85	*390*	**430**	14,896	BOM	
84	*377*	**416**	14,115	BOM	
83	*357*	**394**	13,297	BOM	
82	*370*	**408**	13,355	BOM	
81	*444*	**489**	14,983	BOM	
1980	*489*	**539**	14,404	BOM	
79	*533*	**588**	14,874	BOM	
78	*523*	**576**	12,510	BOM	
77	*473*	**521**	9,543	BOM	
76	*436*	**481**	8,403	BOM	
75	*389*	**429**	6,400	BOM	
74	*435*	**480**	6,306	BOM	
73	*434*	**478**	5,024	BOM	
72	*432*	**476**	5,698	BOM	
71	*350*	**386**	4,559	BOM	

Perlite **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
***1970**	*346,958*	**382,456**	4,321	BOM	
***69**	*361,048*	**397,987**	4,493	BOM	
***68**	*331,559*	**365,481**	3,706	BOM	
***67**	*314,418*	**346,586**	3,424	BOM	
***66**	*311,467*	**343,334**	3,423	BOM	
***65**	*300,288*	**331,011**	2,905	BOM	
***64**	*259,753*	**286,329**	2,568	BOM	
***63**	*235,063*	**259,113**	2,212	BOM	
***62**	*234,202*	**258,164**	2,143	BOM	
***61**	*222,854*	**245,654**	2,159	BOM	
***1960**	*218,262*	**240,593**	2,119	BOM	
***59**	*218,307*	**240,642**	2,121	BOM	
***58**	*183,293*	**202,046**	1,790	BOM	
***57**	*169,878*	**187,259**	1,568	BOM	
***56**	*152,139*	**167,705**	1,271	BOM	
****55**	*134,086*	**147,805**	1,091,250	BOM	
****54**	*100,734*	**111,040**	885,824	BOM	
****53**	*77,012*	**84,891**	661,698	BOM	
52	*W*	**W**	W	BOM	
51	*W*	**W**	W	BOM	
1950	*W*	**W**	W	BOM	
Total					

* mt and st not in thousands
** All values not in thousands

Table 24. **Potash** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Potash **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
2010				EMNRD	
9				EMNRD	
8				EMNRD	
7				EMNRD	
6				EMNRD	
5	**897**	*989*	282,711	EMNRD	
4	**970**	*1,069*	237,819	EMNRD	
3	**966**	*1,065*	202,167	EMNRD	
2	**920**	*1,014*	188,611	EMNRD	
1	**894**	*985*	191,732	EMNRD	
2000	**1,378**	*1,519*	215,738	EMNRD	
99	**1,217**	*1,342*	235,000	USGS	
98	**1,207**	*1,330*	231,000	USGS	
97	**2,450**	*2,701*	240,000	USGS	
96	**2,430**	*2,679*	225,000	USGS	
95	**2,330**	*2,568*	209,000	USGS	
94				BOM	
93				BOM	
92	**1,436**	*1,583*	256,620	BOM	
91	**1,469**	*1,619*	250,900	BOM	
1990	**1,451**	*1,599*	245,571	BOM	
89	**1,365**	*1,505*	242,619	BOM	
88	**1,271**	*1,401*	213,800	BOM	
87	**1,323**	*1,458*	174,200	BOM	
86	**987**	*1,088*	132,900	BOM	
85	**1,120**	*1,235*	156,000	BOM	
84	**1,418**	*1,563*	204,100	BOM	
83	**1,278**	*1,409*	174,700	BOM	
82	**1,497**	*1,650*	204,600	BOM	
81	**1,601**	*1,765*	261,200	BOM	
1980	**1,869**	*2,060*	289,011	BOM	
79	**2,005**	*2,210*	228,776	BOM	
78	**1,943**	*2,142*	183,554	BOM	
77	**1,891**	*2,084*	169,616	BOM	
76	*1,890*	**2,083**	165,354	BOM	
75	*1,587*	**1,749**	150,622	BOM	
74	*1,907*	**2,102**	128,588	BOM	
73	*1,967*	**2,168**	91,996	BOM	
72	*2,083*	**2,296**	91,115	BOM	
71	*2,078*	**2,291**	86,689	BOM	
1970	*2,168*	**2,390**	85,877	BOM	

Potash **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
69	*2,111*	**2,327**	62,034	BOM	
68	*2,077*	**2,289**	63,406	BOM	
67	*2,615*	**2,883**	91,098	BOM	
66	*2,679*	**2,953**	108,653	BOM	
65	*2,584*	**2,848**	117,771	BOM	
64	*2,427*	**2,675**	104,861	BOM	
63	*2,398*	**2,643**	101,458	BOM	
62	*2,003*	**2,208**	85,124	BOM	
61	*2,289*	**2,523**	96,380	BOM	
1960	*2,214*	**2,440**	82,645	BOM	
59	*1,986*	**2,189**	74,117	BOM	
58	*1,794*	**1,978**	69,106	BOM	
57	*1,887*	**2,080**	77,197	BOM	
56	*1,812*	**1,997**	75,122	BOM	
55*	*1,670,238*	**1,841,122**	*?69640740*	BOM	
54*	*1,571,462*	**1,732,240**	*64,366,641*	BOM	
53*	*1,408,704*	**1,552,831**	*58,076,435*	BOM	
52*	*1,280,151*	**1,411,125**	*46,385,452*	BOM	
51*	*1,104,603*	**1,217,617**	*37,209,740*	BOM	
1950**	*973,157*	**1,072,722**	31,944	BOM	
Total					

* Values not in thousands

** mt and st not in thousands

Table 25. **Pumice** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Pumice **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4	**W**	*W*	W	USGS	
3	**W**	*W*	W	USGS	
2	**W**	*W*	W	USGS	
1	**W**	*W*	W	USGS	
2000	**W**	*W*	W	USGS	
99	**W**	*W*	W	USGS	
98	**W**	*W*	W	USGS	
97	**W**	*W*	W	USGS	
96	**102**	*112*	527	USGS	
95	**W**	*W*	W	USGS	
94				BOM	
93				BOM	
92	**W**	*W*	W	BOM	
91	**W**	*W*	W	BOM	
1990	**W**	*W*	W	BOM	
89	**77**	*85*	795	BOM	
****88**	**76,204**	*84,001*	852	BOM	
87	*79*	**87**	991	BOM	
86	*231*	**255**	2,370	BOM	
85	*138*	**152**	1,114	BOM	
84	*120*	**132**	1,269	BOM	
83	*100*	**110**	1,070	BOM	
82	*88*	**97**	809	BOM	
81	*84*	**93**	919	BOM	
1980	*76*	**84**	814	BOM	
79	*547*	**603**	3,550	BOM	
78	*572*	**631**	2,706	BOM	
77	*415*	**457**	1,835	BOM	
76	*441*	**486**	1,560	BOM	
75	*360*	**397**	1,280	BOM	
74	*427*	**471**	1,466	BOM	
73	*308*	**339**	1,001	BOM	
72	*282*	**311**	809	BOM	
71	*260*	**287**	601	BOM	
1970	*184*	**203**	442	BOM	

Pumice **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
69	*205*	**226**	415	BOM	
68	*220*	**243**	527	BOM	
67	*200*	**220**	639	BOM	
66	*222*	**245**	787	BOM	
65	*239*	**264**	915	BOM	
64	*236*	**260**	760	BOM	
63	*292*	**322**	850	BOM	
62	*279*	**308**	741	BOM	
61	*308*	**339**	879	BOM	
1960	*331*	**365**	827	BOM	
59	*447*	**493**	1,023	BOM	
58	*460*	**507**	959	BOM	
57	*291*	**321**	756	BOM	
56*	*265,197*	**292,330**	667,146	BOM	
55*	*357,065*	**393,597**	780,339	BOM	
54*	*330,148*	**363,926**	1,060,096	BOM	
53*	*479,582*	**528,649**	759,840	BOM	
52*	*197,296*	**217,482**	755,139	BOM	
51*	*222,772*	**245,564**	884,311	BOM	
1950**	*319,004*	**351,642**	1,110	BOM	
Total					

* Values not in thousands

** mt and st not in thousands

Table 26. **Rare earth minerals** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Rare Earth Minerals **Year**	**10^3 mt**	**10^3 st**	**10^3 \$**	**Sources**	Remarks
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	
71				BOM	

Rare Earth Minerals Year	10^3 mt	10^3 st	10^3 $	Sources	Remarks
1970				BOM	
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 27. **Salt** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Salt **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4	*W*	**W**	W	USGS	
3	*W*	**W**	W	USGS	
2	*W*	**W**	W	USGS	
1	*W*	**W**	W	USGS	
2000	*W*	**W**	W	USGS	
99				USGS	
98	*W*	**W**	W	USGS	
97	*W*	**W**	W	USGS	
96	*W*	**W**	W	USGS	
95	*W*	**W**	W	USGS	
94				BOM	
93				BOM	
92	*W*	**W**	W	BOM	
91	*W*	**W**	W	BOM	
1990	*W*	**W**	W	BOM	
89	*W*	**W**	W	BOM	
88	*W*	**W**	W	BOM	
87	*W*	**W**	W	BOM	
86	*W*	**W**	W	BOM	
85	*W*	**W**	W	BOM	
84	*W*	**W**	W	BOM	
83	*W*	**W**	W	BOM	
82	*W*	**W**	W	BOM	
81	*W*	**W**	W	BOM	
1980	*W*	**W**	W	BOM	
79	*W*	**W**	W	BOM	
78	*163*	**180**	1,617	BOM	
77	*W*	**W**	W	BOM	
76	*W*	**W**	W	BOM	
75	*133*	**147**	1,048	BOM	
74	*151*	**167**	W	BOM	
73	*W*	**W**	W	BOM	
72	*W*	**W**	W	BOM	
71	*132*	**146**	1,130	BOM	
1970	*W*	**W**	W	BOM	

Salt **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
69	*W*	**W**	W	BOM	
68	*W*	**W**	W	BOM	
67	*74*	**82**	1,036	BOM	
66	*60*	**66**	716	BOM	
65	*58*	**64**	572	BOM	
64	*56*	**62**	559	BOM	
63	*49*	**54**	472	BOM	
62	*39*	**43**	334	BOM	
61	*30*	**33**	284	BOM	
1960	*35*	**39**	331	BOM	
59	*33*	**36**	322	BOM	
58	*28*	**31**	275	BOM	
57	*48*	**53**	429	BOM	
56	*52*	**57**	501	BOM	
***55**	*45,122*	**49,738**	596,780	BOM	
***54**	*45,966*	**50,669**	333,255	BOM	
***53**	*56,324*	**62,087**	216,364	BOM	
52	*W*	**W**	W	BOM	
51	*W*	**W**	W	BOM	
1950	*W*	**W**	W	BOM	
Total					

* Values not in thousands

Table 28. **Sand and gravel** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Sand & Gravel Year	10^3 mt	10^3 st	10^3 $	Sources	Remarks
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4	**13,600**	*14,991*	89,500	USGS	
3	**13,300**	*14,661*	65,300	USGS	
2	**12,800**	*14,110*	62,600	USGS	
1	**10,600**	*11,685*	54,500	USGS	
2000	**13,400**	*14,771*	66,800	USGS	
99	**10,600**	*11,685*	53,000	USGS	
98	**11,100**	*12,236*	53,300	USGS	
97	**9,390**	*10,351*	46,600	USGS	
96	**9,880**	*10,891*	48,500	USGS	
95	**10,400**	*11,464*	50,700	USGS	
94				BOM	
93				BOM	
92	*10,170*	**11,210**	46,176	BOM	
91	*8,346*	**9,200**	35,900	BOM	
1990	*9,354*	**10,311**	39,631	BOM	
89	*10,705*	**11,800**	45,400	BOM	
88	*7,971*	**8,787**	31,367	BOM	
87	*7,802*	**8,600**	31,000	BOM	
86	*7,685*	**8,471**	25,862	BOM	
85	*7,620*	**8,400**	22,800	BOM	
84	*7,587*	**8,363**	22,389	BOM	
83	*6,350*	**7,000**	20,000	BOM	
82	*5,095*	**5,616**	17,670	BOM	
81	*5,893*	**6,496**	19,780	BOM	
1980	*6,396*	**7,050**	17,676	BOM	
79	*6,478*	**7,141**	18,245	BOM	
78	*7,474*	**8,239**	17,850	BOM	
77	*7,805*	**8,604**	17,685	BOM	
76	*6,987*	**7,702**	16,671	BOM	
75	*5,643*	**6,220**	13,798	BOM	
74	*6,725*	**7,413**	10,605	BOM	
73	*9,653*	**10,641**	15,753	BOM	
72	*6,895*	**7,600**	8,553	BOM	
71	*8,046*	**8,869**	7,975	BOM	

Sand & Gravel **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
1970	*9,676*	**10,666**	10,516	BOM	
69	*7,778*	**8,574**	10,422	BOM	
68	*11,124*	**12,262**	12,396	BOM	
67	*13,310*	**14,672**	14,336	BOM	
66	*14,064*	**15,503**	13,029	BOM	
65	*10,671*	**11,763**	12,130	BOM	
64	*7,966*	**8,781**	10,160	BOM	
63	*7,622*	**8,402**	12,843	BOM	
62	*6,250*	**6,889**	8,021	BOM	
61	*11,361*	**12,523**	10,049	BOM	
1960	*6,730*	**7,419**	7,459	BOM	
59	*11,304*	**12,460**	13,332	BOM	
58	*11,979*	**13,205**	11,413	BOM	
57	*7,249*	**7,991**	7,803	BOM	
56	*5,493*	**6,055**	5,776	BOM	
***55**	*4,133,539*	**4,556,447**	6,004,554	BOM	
***54**	*5,914,244*	**6,519,339**	8,340,251	BOM	
***53**	*1,284,918*	**1,416,380**	1,238,979	BOM	
***52**	*450,799*	**496,921**	499,589	BOM	
***51**	*979,992*	**1,080,256**	1,087,857	BOM	
1950	*851*	**938**	923	BOM	
Total					

* Values not in thousands

Table 29. **Scoria** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Scoria **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
2010				EMNRD	
9				EMNRD	
8				EMNRD	
7				EMNRD	
6				EMNRD	
5	*441*	**486**	7,630	EMNRD	
4	*475*	**524**	7,853	EMNRD	
3	*323*	**356**	5,659	EMNRD	
2	*424*	**467**	5,736	EMNRD	
1	*456*	**502**	6,009	EMNRD	
2000	*304*	**335**	4,873	EMNRD	
99	272		4,028	EMNRD	
98	328		3,341	EMNRD	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	
71				BOM	
1970				BOM	

Scoria Year	10^3 mt	10^3 st	10^3 \$	Sources	Remarks
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 30. **Sillimanite** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Sillimanite **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	Remarks
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	
71				BOM	
1970				BOM	

Sillimanite Year	10^3 mt	10^3 st	10^3 \$	Sources	Remarks
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 31. **Silica** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Silica **Year**	**10^3 mt**	**10^3 st**	**10^3 \$**	**Sources**	Remarks
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1	W	W	W	USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	
71				BOM	

Silica **Year**	**10^3 mt**	**10^3 st**	**10^3 \$**	**Sources**	Remarks
1970				BOM	
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 32. **Stone (carvable)** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Stone (carvable) **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	
71				BOM	

Stone (carvable) Year	10^3 mt	10^3 st	10^3 $	Sources	Remarks
1970				BOM	
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 33. **Stone (crushed)** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Stone (crushed) **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4	**3,430**	*3,781*	24,400	USGS	
3	**3,730**	*4,112*	26,000	USGS	
2	**3,680**	*4,057*	23,300	USGS	
1	**4,230**	*4,663*	26,100	USGS	
2000	**3,690**	*4,068*	22,400	USGS	
99	**3,710**	*4,090*	22,200	USGS	
98	**4,700**	*5,181*	28,200	USGS	
97	**2,920**	*3,219*	15,700	USGS	
96	**3,480**	*3,836*	18,800	USGS	
95	**3,660**	*4,034*	18,800	USGS	
94				BOM	
93				BOM	
92	*2,722*	**3,000**	14,400	BOM	
91	*2,541*	**2,801**	13,089	BOM	
1990	*2,177*	**2,400**	12,800	BOM	
89	*2,526*	**2,784**	11,672	BOM	
88	*3,175*	**3,500**	13,900	BOM	
87	*4,085*	**4,503**	15,919	BOM	
86	*3,538*	**3,900**	15,300	BOM	
85	*3,303*	**3,641**	15,232	BOM	
84	*4,264*	**4,700**	17,000	BOM	
83	*4,291*	**4,730**	15,118	BOM	
82	*2,540*	**2,800**	13,700	BOM	
81	*3,776*	**4,162**	12,485	BOM	
1980	*2,341*	**2,581**	9,473	BOM	
79	*2,349*	**2,589**	6,743	BOM	
78	*2,212*	**2,438**	6,157	BOM	
77	*1,769*	**1,950**	4,786	BOM	
76	*1,743*	**1,921**	4,289	BOM	
75				BOM	
74	*3,203*	**3,531**	8,359	BOM	
73				BOM	
72				BOM	
71	*2,643*	**2,913**	5,337	BOM	

Stone (crushed) Year	10^3 mt	10^3 st	10^3 \$	Sources	Remarks
1970	*2,812*	**3,100**	4,030	BOM	
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55*				BOM	
54*				BOM	
53*				BOM	
52*				BOM	
51*				BOM	
1950				BOM	
Total					

Table 34. **Stone (dimension)** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Stone (dimension) **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4	**57**	*63*	2,430	USGS	
3	**57**	*63*	2,590	USGS	
2	**20**	*22*	1,370	USGS	
1	**36**	*40*	1,320	USGS	
2000	W	W	W	USGS	
99	18	*20*	2,320	USGS	
98	*W*	**W**	W	USGS	
97	*W*	**W**	W	USGS	
96	*W*	**W**	W	USGS	
95	*W*	**W**	W	USGS	
94	*W*	**W**	W	BOM	
93	*W*	**W**	W	BOM	
92	*W*	**W**	W	BOM	
91	*W*	**W**	W	BOM	
1990	*W*	**W**	W	BOM	
89	*W*	**W**	W	BOM	
88*	*19,861*	**21,893**	626	BOM	
87*	*19,861*	**21,893**	626	BOM	
86*	*19,609*	**21,615**	378	BOM	
85	*18*	**20**	277	BOM	
84	*18*	**20**	185	BOM	
83	*16*	**18**	141	BOM	
82	*16*	**18**	138	BOM	
81	*24*	**26**	173	BOM	
1980	*16*	**18**	91	BOM	
79	*18*	**20**	117	BOM	
78	*16*	**18**	115	BOM	
77	*15*	**17**	106	BOM	
76	*13*	**14**	105	BOM	
***75**				BOM	
74	*W*	**W**	W	BOM	
***73**				BOM	
***72**				BOM	
71	*W*	**W**	W	BOM	

Stone (dimension) **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
1970	*W*	**W**	W	BOM	
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

* Values combined with crushed under Stone undifferentiated

Table 35. **Stone (decorative)** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Stone (decorative) Year	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	
71				BOM	

Stone (decorative) Year	10^3 mt	10^3 st	10^3 \$	Sources	Remarks
1970				BOM	
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 36. **Stone (undifferentiated)** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Stone (undifferentiated) **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4				USGS	
3				USGS	
2				USGS	
1				USGS	
2000				USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75	*1,993*	**2,197**	4,683	BOM	
74				BOM	
73	*2,567*	**2,830**	5,894	BOM	
72	*2,511*	**2,768**	5,499	BOM	
71				BOM	

Stone (undifferentiated) **Year**	**10³ mt**	**10³ st**	**10³ $**	**Sources**	**Remarks**
1970				BOM	
69	*2,564*	**2,826**	3,286	BOM	
68	*2,019*	**2,226**	3,527	BOM	
67	*1,262*	**1,391**	2,403	BOM	
66	*2,406*	**2,652**	4,056	BOM	
65	*1,734*	**1,911**	3,020	BOM	
64	*2,504*	**2,760**	4,244	BOM	
63	*2,276*	**2,509**	4,236	BOM	
62	*1,818*	**2,004**	2,782	BOM	
61	*1,681*	**1,853**	2,206	BOM	
1960	*1,158*	**1,277**	1,692	BOM	
59	*418*	**461**	542	BOM	
58	*1,569*	**1,730**	1,507	BOM	
57	*1,223*	**1,348**	1,618	BOM	
56	*1,150*	**1,268**	1,272	BOM	
***55**	*1,427,402*	**1,573,441**	1,546,665	BOM	
***54**	*700,011*	**771,630**	714,037	BOM	
***53**	*566,562*	**624,528**	510,713	BOM	
***52**	*288,389*	**317,894**	191,642	BOM	
***51**	*927,960*	**1,022,901**	592,179	BOM	
1950	*331*	**365**	244	BOM	
Total					

* Values not in thousands

Individual Minerals (p. 73)

Table 37. **Sulfur** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Sulfur Year	10^3 mt	10^3 st	10^3 \$	Sources	Remarks
2010				USGS	
9				USGS	
8				USGS	
7				USGS	
6				USGS	
5				USGS	
4	*W*	**W**	W	USGS	
3	*W*	**W**	W	USGS	
2	*W*	**W**	W	USGS	
1	*W*	**W**	W	USGS	
2000	*W*	**W**	W	USGS	
99				USGS	
98				USGS	
97				USGS	
96				USGS	
95				USGS	
94				BOM	
93				BOM	
92				BOM	
91				BOM	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	
71				BOM	
1970				BOM	

Sulfur **Year**	**10^3 mt**	**10^3 st**	**10^3 $**	**Sources**	**Remarks**
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56	*W*	**W**	W	BOM	
55	*W*	**W**	W	BOM	
54	*W*	**W**	W	BOM	
53	*W*	**W**	W	BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Table 38. **Zeolite** production by year in metric tons (mt), short tons (st) and total value in dollars. Bold=reported; italics=calculated. W=Produced, but specific data not available or information withheld.

Zeolite Year	mt	st	$10^3 \$$	Sources	Remarks
2010					
9					
8					
7					
6	*28,595*	**31,520**	W	Producer(s)	
5	*27,638*	**30,465**	W	Producer(s)	
4	*21,389*	**23,577**	W	Producer(s)	
3	*15,474*	**17,057**	W	Producer(s)	
2	*14,273*	**15,733**	W	Producer(s)	
1	*14,471*	**15,951**	W	Producer(s)	
2000	*14,898*	**16,422**	W	Producer(s)	
99	*14,432*	**15,908**	W	Producer(s)	
98	*12,787*	**14,095**	W	Producer(s)	
97	*13,620*	**15,013**	W	Producer(s)	
96	*13,114*	**14,456**	W	Producer(s)	
95	*18,847*	**20,775**	W	Producer(s)	
94	*18,979*	**20,921**	W	Producer(s)	
93	*12,686*	**13,984**	W	Producer(s)	
92	*4,359*	**4,805**	W	Producer(s)	
91	*1,676*	**1,848**	W	Producer(s)	
1990				BOM	
89				BOM	
88				BOM	
87				BOM	
86				BOM	
85				BOM	
84				BOM	
83				BOM	
82				BOM	
81				BOM	
1980				BOM	
79				BOM	
78				BOM	
77				BOM	
76				BOM	
75				BOM	
74				BOM	
73				BOM	
72				BOM	
71				BOM	
1970				BOM	

Zeolite **Year**	**mt**	**st**	**10^3 $**	**Sources**	**Remarks**
69				BOM	
68				BOM	
67				BOM	
66				BOM	
65				BOM	
64				BOM	
63				BOM	
62				BOM	
61				BOM	
1960				BOM	
59				BOM	
58				BOM	
57				BOM	
56				BOM	
55				BOM	
54				BOM	
53				BOM	
52				BOM	
51				BOM	
1950				BOM	
Total					

Montana's Industrial Minerals

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ABSTRACT

Industrial minerals production in Montana is severely limited by the distance to major markets, but despite this handicap certain segments of the industry are thriving by serving local markets or because the commodity has sufficient value to support greater shipping costs. Montana continues to be the leading talc-producing state measured both in value and quantity of talc produced. At present, talc is mined in three open pits, all in southwestern Montana where high-purity talc was formed by hydrothermal replacement of Archean marble.

Major markets for Montana talc include pitch control in the manufacture of paper and the manufacture of ceramic substrates for catalytic converters used in cars and trucks. The one known chlorite deposit in Montana has been mined out; however, there is potential for discovery of other chlorite deposits in the Archean rocks of southwestern Montana. Limestone is quarried for two cement plants and also for two lime plants. These quarries are all in the Mississippian Madison Group that is the major source of high-calcium limestone. Garnets derived from Archean gneisses and schists are concentrated in several alluvial deposits in southwestern Montana. They are mined from a deposit in the Virginia City area where these garnets are processed for the sand blast, water jet, and filter-bed media markets. Also, a recently permitted garnet operation in the Dillon area will produce water jet-cutting media from garnetiferous tailings of a former tungsten mill.

Scenic areas in northwestern and southwestern Montana have experienced significant growth that has led to an increase in aggregate consumption. Just east of Butte a fine-grained igneous rock is quarried for ballast. The highly fragmented decorative stone industry in Montana has grown significantly in recent years with a large production of metasedimentary rock quarried from the Belt Supergroup. Production is from many small quarries in northwestern Montana and is destined for both local and out-of-state markets. Cretaceous sandstone (some classed as field stone and some as moss rock) is quarried in central Montana. River rock is picked both in southwestern Montana and in northwestern Montana. Recently, interest has been shown in Montana's barite deposits that form veins in the Belt Supergroup of western Montana. There is also renewed interest in bentonite deposits in the central and eastern parts of the state where these beds occur in Cretaceous formations. Undeveloped industrial mineral deposits in Montana include white marble, clinoptilolite, silica sand, gypsum, and vermiculite.

INTRODUCTION

Because of the diversity of Montana's geology, there are a variety of nonmetallic mineral resources in the state. However, in common with several other western states, lack of local markets and transportation cost has hindered the development of some of these resources such as glass sand and quartz for silicon carbide manufacture. Others, such as talc and some decorative stone, have overcome this disadvantage because the value of these materials enables their pricing to accommodate transport to West Coast, or even in the case of talc, to some foreign markets.

In this paper, we attempt to accomplish the following.

1. Present the status of industrial mineral development and production in Montana.
2. Provide information on the geologic setting and geologic controls on the distribution of the industrial minerals discussed.
3. Provide our assessment of the potential for discovery of new deposits of selected industrial minerals.

We have not attempted to include all the industrial minerals that are known to occur in Montana or even all of those that have been produced. Rather our discussion is limited to those that are either now being produced or that have identifiable potential for future production. For a more nearly complete listing of industrial minerals in Montana see United States Geological Survey and Montana Bureau of Mines and Geology (1963) or for a more recent, but less exhaustive list see Berg (1990).

BARITE

Because essentially all of the barite that has been mined in Montana was used as a weighting agent in drilling mud, production has generally been controlled by the needs of the oil and gas industry. Barite was mined for this market from 1951 until 1966 and again in 1976 with continued production into the 1990's. There is no current production, but with increased demand by the oil and gas industry there is renewed interest in these deposits.

Although there are many barite occurrences in western Montana, only those in meta-sedimentary rocks of the Proterozoic Belt Supergroup have been mined (Berg, 1988). Barite veins in these rocks are generally steeply dipping and of high purity; quartz and fragments of the wall rock are the major impurities. The greatest concentration of mineable barite veins is in the Elk Creek – Coloma area 30 miles east of Missoula (fig. 1) which is also responsible for most of the historic production. In this district, veins are situated in quartzite of the Belt Supergroup close to the contact with a Cretaceous granitic pluton. Barite has been mined in seven open cuts and one underground mine, the Elk Creek mine, which is responsible for most of the production from this district. The barite vein in the Elk Creek mine is reported to range up to 27 ft thick with an average thickness of 12 ft. Barite mined in the period from 1976 into the 1980s from these veins required only pulverizing in a roller mill before being sold for use as a weighting agent in drilling mud. The Elk Creek – Coloma district seems to offer the greatest possibility for the development and discovery of additional mineable reserves.

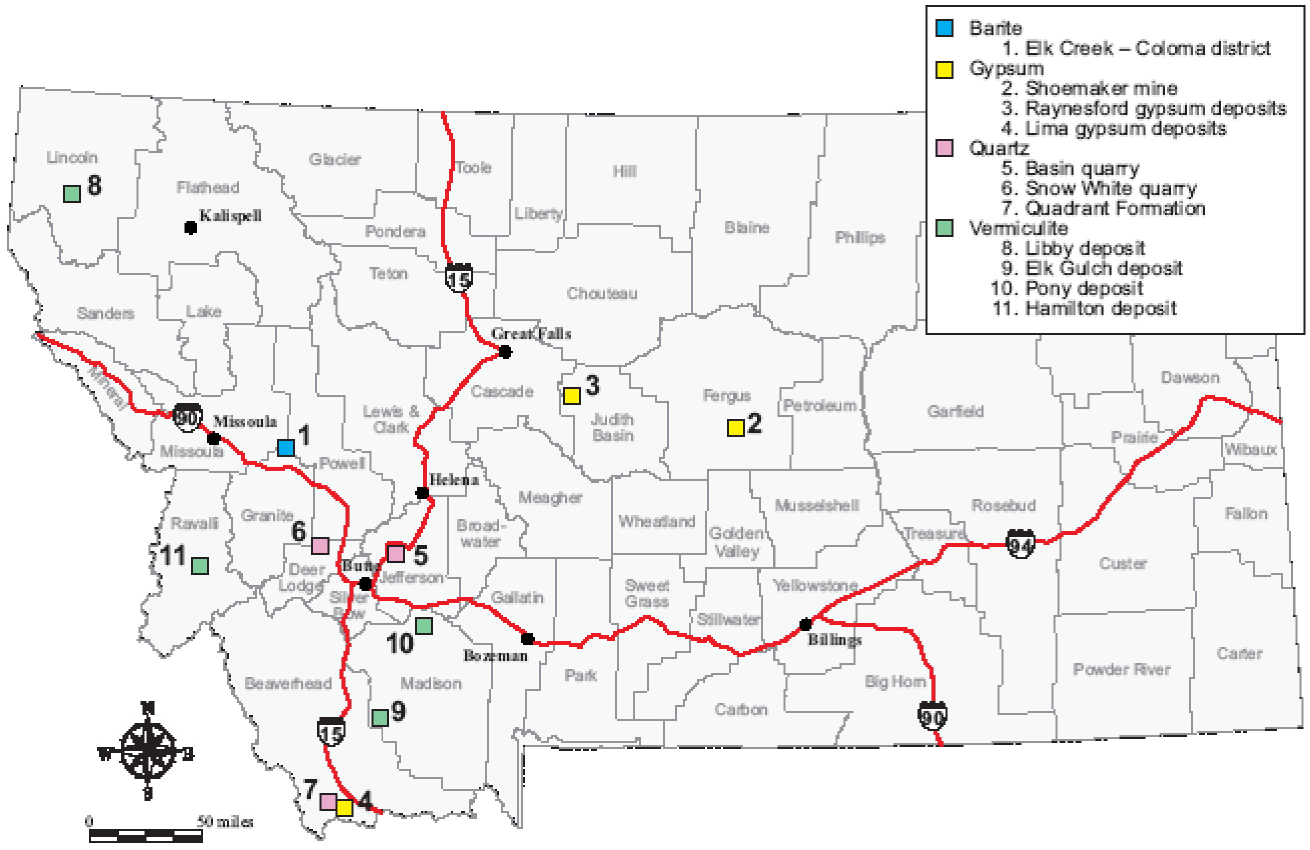

Figure 1. Barite, gypsum, quartz, and vermiculite deposits. See descriptions in text under respective headings.

BENTONITE

Bentonite has been mined from the marine Cretaceous formations of central and eastern Montana for all of the major markets including pet litter, drilling mud, engineering applications, taconite pelletizing, and bonding for foundry molding sand. Extreme southeastern Montana, on the flank of the Black Hills uplift, has been the source of most bentonite production in Montana where both American Colloid and Bentonite Performance Minerals now mine bentonite (fig. 2). Additionally, Wyo – Ben mines bentonite from the Mowry Shale in Carbon County and American Colloid also mines bentonite in this area. Significant quantities of bentonite have been mined from the Bearpaw Shale in the Vananda area, south of Malta and south of Glasgow.

Substantial deposits of bentonite in the Bearpaw Shale underlie much of north central Montana. The two bentonite beds that have been mined in the Vananda area are approximately three ft thick and are separated by 7 to 11 ft of shale (Berg, 1970). A general overview of bentonite deposits in Montana is provided by Berg (1969); detailed information on the deposits in extreme southeastern Montana can be found in Knechtel and Patterson (1962) and similar information on the deposits in the Hardin district southeast of Billings is in Knechtel and Patterson (1956). Wolfbauer (1977, 1978) provides information on exchangeable cations in bentonite from the vicinity of the Fort Peck Reservoir in northeastern Montana.

Bentonite also occurs in nonmarine Tertiary beds of the intermontane valleys of southwestern Montana (fig. 2). However these beds are less continuous than the marine Cretaceous beds, and in some instances contain a larger non-clay detrital fraction that makes them unsuitable for the markets available to the Cretaceous bentonites. They have been mined for local use such as sealing ponds and ditches.

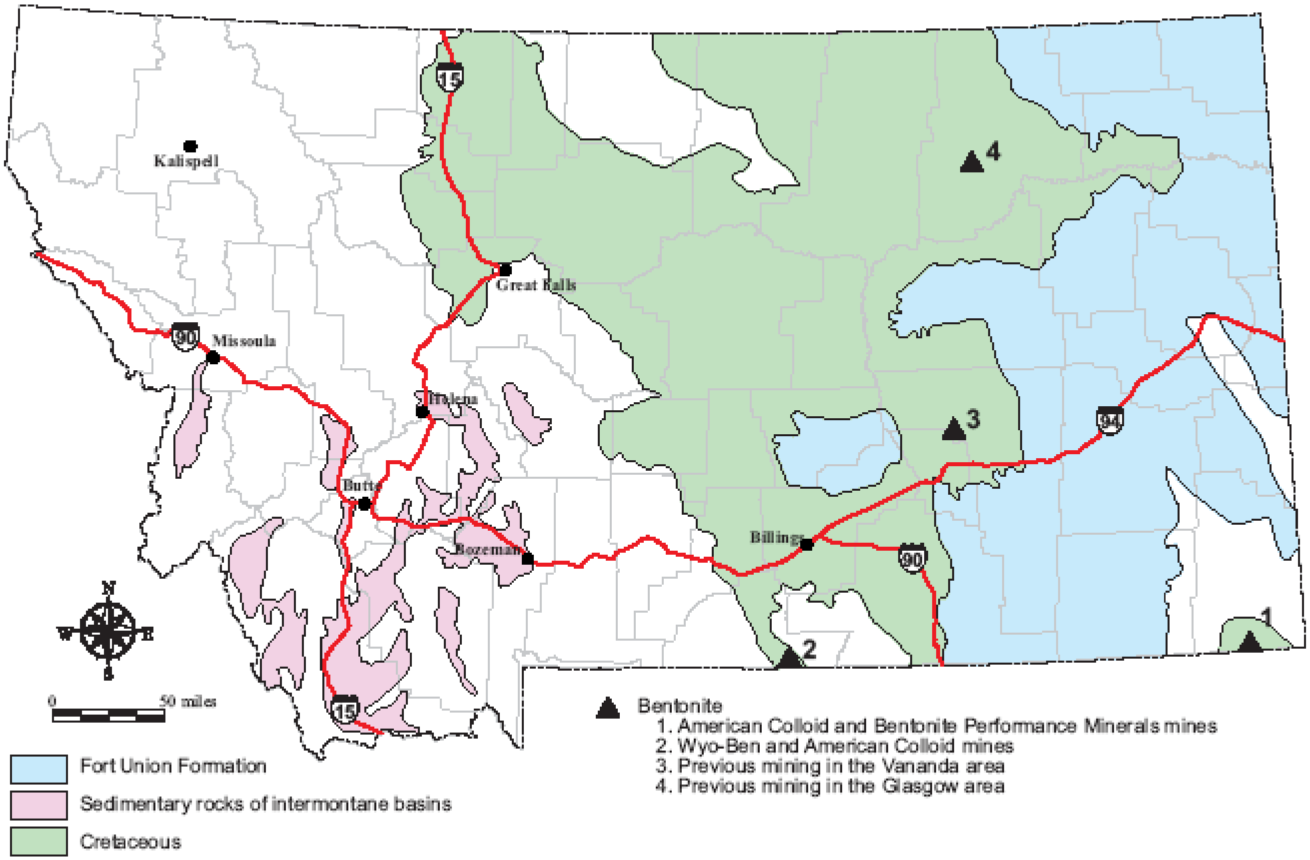

Figure 2. Bentonite deposits that have been mined or are being mined. Base map from Berg, 1969.

CHLORITE

Magnesian chlorite was mined at the Antler Mine, located 25 miles southeast of Butte, from 1976 until 1999 when the ore body was mined out (fig. 3); the mine has now been reclaimed. Approximately 250,000 short tons of hand-sorted chlorite from this deposit were processed by Cyprus Industrial Minerals and then by Luzenac America, Inc. for the paint and ceramics markets (Berg and Crouse, 2001). Subparallel chlorite veins from less than 10 ft to almost 30 ft wide were mined in an open pit. Chlorite veins were formed by introduction of magnesium-bearing hydrothermal solutions that essentially completely replaced Precambrian quartzofeldspathic gneiss to produce a high-purity deposit. Associated chlorite and talc deposits in southwestern Montana show that where magnesian-bearing hydrothermal fluids encountered marble, talc was formed; where they encountered an aluminous rock such as quartzofeldspathic gneiss, chlorite was formed. According to this interpretation, both talc and chlorite deposits are Proterozoic and are co-genetic.

Chloritic alteration of Precambrian gneiss occurs along faults in the Ruby Range adjacent to the Sweetwater Basin in southwestern Montana and also in the Rochester area south of the Antler mine (Berg, 1992 and 1996), but neither occurrence is economic. Exploration by talc producers and the Montana Bureau of Mines and Geology has failed to find another mineable chlorite deposit in southwestern Montana, but potential for future discoveries is regarded as reasonably good.

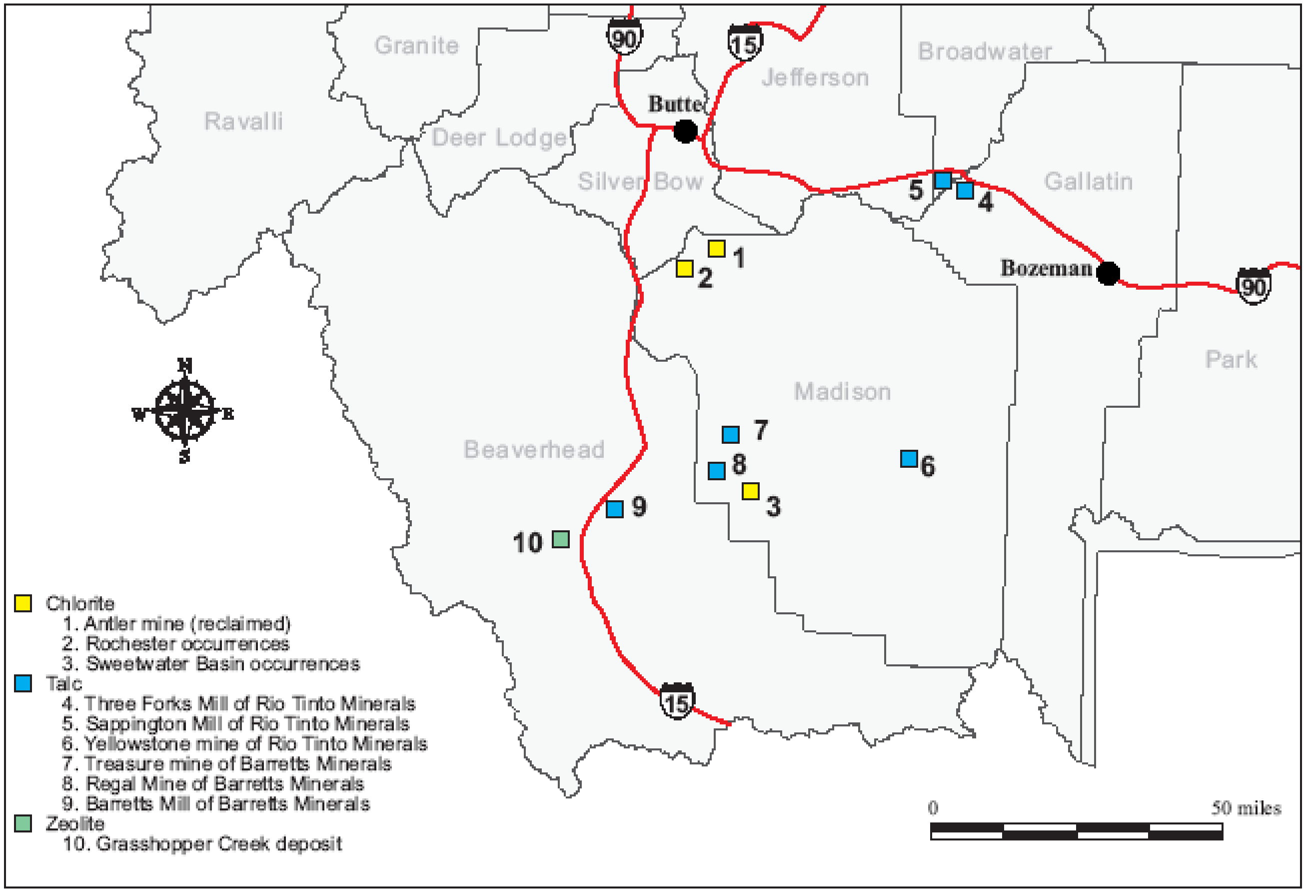

Figure 3. Chlorite, talc, and zeolite mines, mills, deposits, and occurrences.

GARNET

Garnet resources occur in Archean gneisses, garnet-rich contact metamorphic rocks, and placer deposits derived from these sources. Bucket-line gold dredges processed gravels from Alder and Brown gulches near the beginning of the twentieth century (fig. 4). Resulting dredge tailings of a few million yards contain 6 to 7 percent almandine garnet. Alluvial deposits along streams flowing into the Ruby River in the same general area contain as much as 50 percent garnet locally. Testing has revealed resources of a few million cubic yards in the few drainages tested. Currently, Ruby Valley Garnet mines and processes garnet from an alluvial deposit in this same area for the water-jet-cutting and filter-bed markets. Also in this area, Barton Gulch contains coarse garnets in Tertiary placer deposits (lower end) while placers in the upper end of the drainage contain small garnets derived from the Archean gneiss. Gold placer tests have indicated potential garnet resources in the soils and placer gravels of Harris and Californian creeks on the west flank of the Tobacco Root Mountains where garnets are derived from both Archean gneisses and skarns (fig. 4). The Sweetwater drainage in the headwaters of the Ruby River contains alluvial garnet resources that have been documented by a number of exploration programs.

Southwest of Butte, tungsten mines that operated in skarn deposits near Browns Lake (fig.4) have yielded several million tons of tailings that are 85 percent garnet. Fortuitously, these tailings were ground to the size needed for water-jet-cutting media, and plans are underway to process these tailings to recover both garnet and tungsten. Lode deposit resources from this skarn deposit can be projected to be in excess of 25 million tons of garnet-tungsten ore. The placer potential of the area is untested.

Because of the great extent of the garnet-rich Archean gneiss in southwestern Montana there are significantly more untested potential alluvial and lode deposits than those that have been tested. Van Gosen and others (1998) provide additional information on the garnet potential of southwestern Montana.

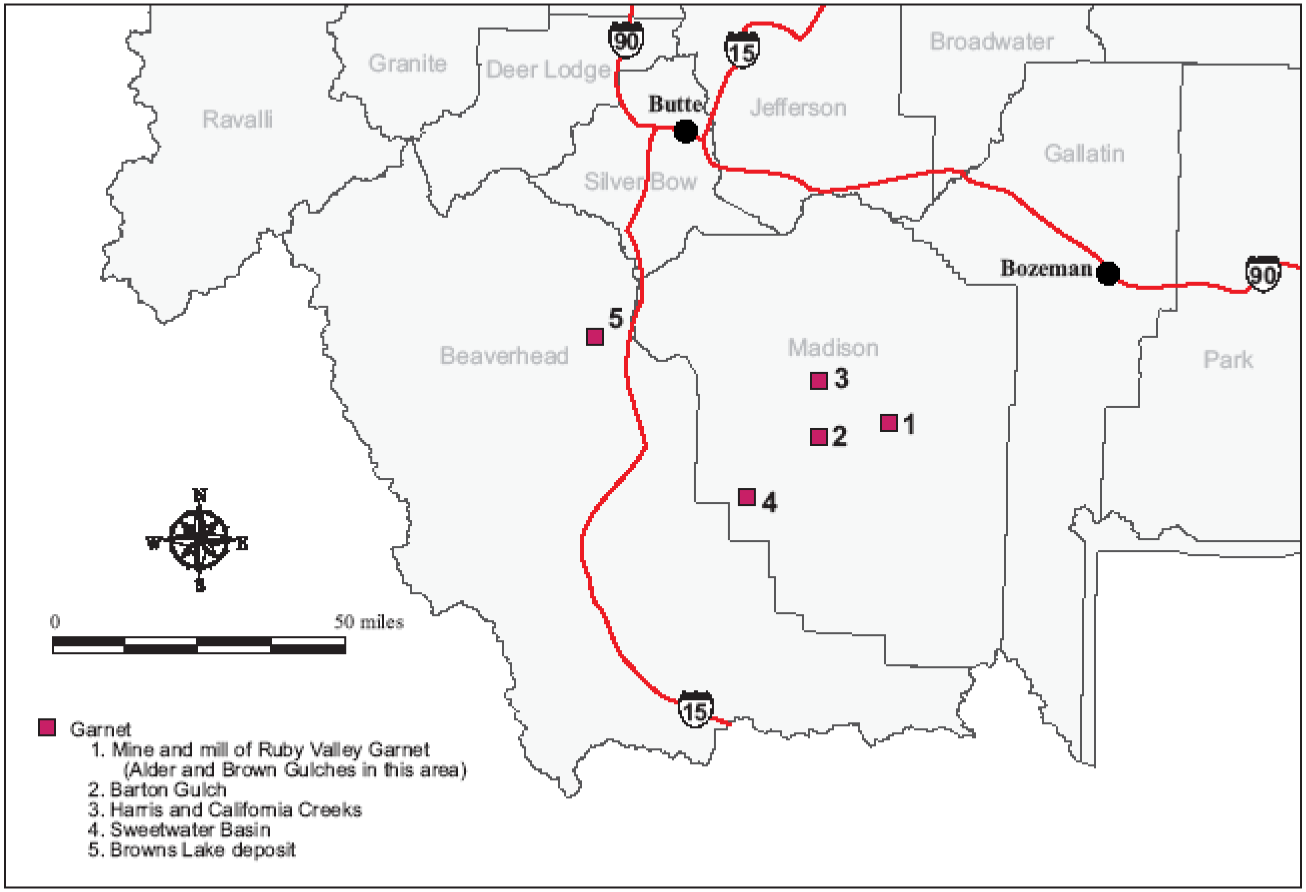

Figure 4. Garnet operations, deposits, and occurrences.

GEMSTONES

Sapphires

Montana is well known in gemstone circles for its sapphire deposits, particularly the blue sapphires from the Yogo deposit in central Montana about 40 miles southwest of Lewistown (fig. 5). At this deposit sapphires have been mined from an altered lamprophyre dike in addition to accompanying placer deposits. Yogo Creek Mining discontinued mining in 2005 because the dike rock that they encountered was too hard to effectively recover sapphires economically. However, within the past year mining sapphires in this underground mine has been resumed by other individuals on a smaller scale. If the ownership of the Yogo district were consolidated, it is possible that further mineable reserves of these sapphires could be developed. Because of the natural uniformly blue color of sapphires from the Yogo deposit and their general lack of inclusions, these sapphires command a premium in the gemstone market. Additional lamprophyre dikes are known in central Montana, and it is very unlikely that most of them have been evaluated for sapphires. A well-planned exploration program in this area might lead to the discovery of another source of blue sapphires.

During the early part of the 20th century, sapphires were mined from alluvial deposits in southwestern Montana mainly for watch and instrument bearings, with only minor gemstone use. At least 45 short tons of sapphires have been mined from these alluvial deposits. With the introduction of synthetic sapphire, this market for natural sapphires was eliminated and sapphires were produced only for the gemstone market. Because most of these sapphires are of pale color, the gemstone market was quite limited until the advent of heat treating. Color of most of these sapphires can be enhanced by heating under carefully controlled conditions.

Alluvial sapphires have been produced from terraces along the Missouri River east of Helena (Clabaugh, 1952), alluvium along the South Fork of Dry Cottonwood Creek northwest of Butte (Berg, in press), and from very large alluvial deposits in the Rock Creek (Gem Mountain) district 55 miles northwest of Butte (Clabaugh, 1952) (fig 5). It is thought that Tertiary volcanic rocks were the bedrock source for these sapphires. More than 20 purported occurrences of sapphires are found in southwestern Montana, most of which have received little or no evaluation.

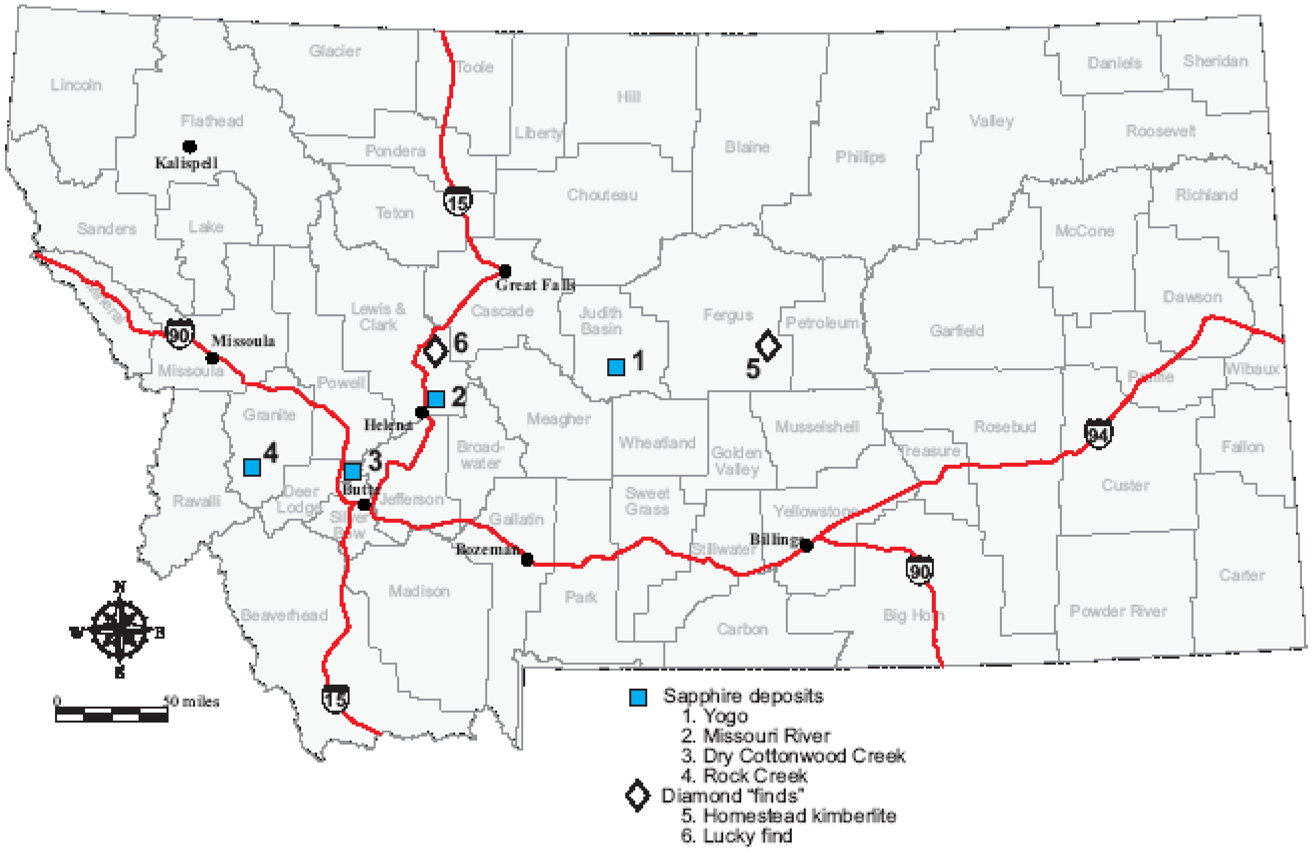

Figure 5. Gemstone deposits and finds.

Diamonds

Mafic alkalic igneous rocks are found throughout central Montana, including some with kimberlitic affinities. One of these is a true kimberlite that is situated near Grass Range, a small settlement in central Montana (fig. 5). This kimberlite pipe, the Homestead kimberlite, yielded a micro-diamond 0.14 by 0.16 by 0.32 mm (Ellsworth, 2000). This is the only verified occurrence of a diamond in a kimberlite in Montana.

An intriguing find of a 14-carat yellow, gem-quality diamond was made along a gravel road in the Craig area south of Great Falls. It was reported that an investigation of the gravel used in surfacing this road failed to find any additional diamonds. A large area of central and eastern Montana is underlain by the Archean Wyoming Province that is generally considered conducive to the presence of diamondiferous kimberlites.

Semiprecious Gemstones

Agate, locally known as Montana moss agate, is found in the gravel along the Yellowstone River from Billings downstream eastward. The most prized specimens of this agate contain black manganese minerals that produce attractive patterns when the agate is slabbed and polished. Smoky quartz and amethyst are collected from pegmatites in granite in the Butte area.

GYPSUM

Underground mining of gypsum beds in the Jurassic Ellis Group at the Shoemaker Mine nine miles southeast of Lewistown (fig. 1) was begun in 1916 (Perry, 1949). In 1928, U.S. Gypsum bought the mine and in 1936 constructed a wallboard plant next to the mine. Production of wallboard continued until 1987, when the mine and plant were closed primarily because of the high cost of underground mining and cost of shipping wallboard to markets outside of Montana.

Farther to the west, gypsum was formerly mined from beds in the Mississippian Kibbey Formation about six miles southeast of Great Falls in the Raynesford area. This gypsum was sold to the Montana cement producers during the 1990s, but is not now being mined.

Several gypsum deposits have been described in the Mississippian Big Snowy Group south of Dillon near Lima (Johns, 1980) (fig.1). There has been only very limited mining of these deposits.

LIMESTONE

The state contains extensive limestone deposits of varying purity. The majority of the industrial production has focused on two geologic units. Historic production of burnt lime has consistently been from the Mississippian Mission Canyon Formation of the Madison Group, in which purity typically exceeds 98 percent $CaCO_3$. Graymont Western U.S. quarries the Mission Canyon Formation for production of lime at their Indian Creek plant (fig. 6). Montana Limestone Company also quarries limestone from the Mission Canyon Formation at their Warren Quarry for lime manufacture at the Frannie Lime Plant just across the border in Wyoming. Holcim's cement plant at Trident produces from the Lodgepole Formation of the Madison Group (Chelini, 1965) and the Ash Grove Cement West's plant at Montana City also uses limestone quarried from the Madison Group. The cement plants have production capacity for processing about 1 million tons of limestone per year (McCulloch, 2001). Former quarry sites that have not seen industrial activity for more than 50 years have railroad access and offer potential for development. Although the limestone resource is potentially extensive, the distance to markets is the deterrent to increased production.

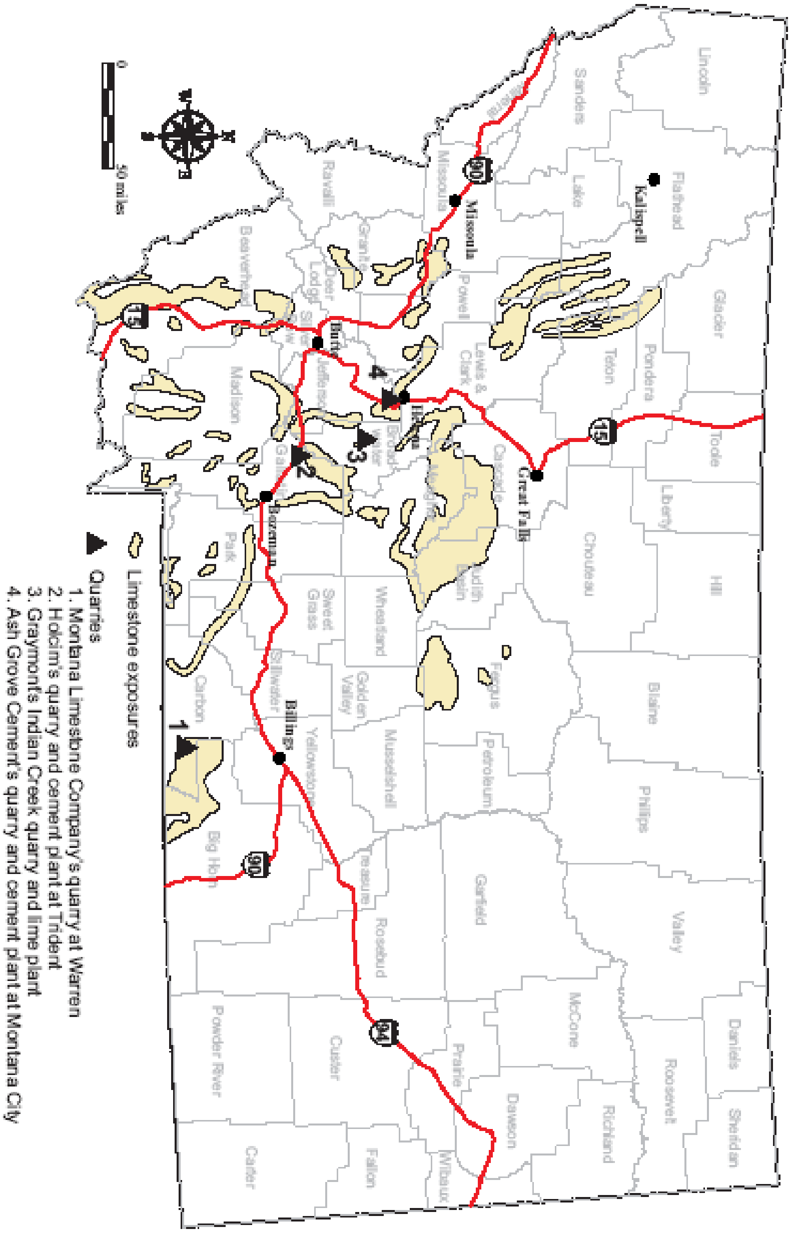

Figure 6. Exposures and quarries of Paleozoic limestone from U.S.Geological Survey and Montana Bureau of Mines and Geology Special Publication 28.

QUARTZ

Two quartz deposits in Montana have been mined for metallurgical use during the 1960s and early 1970s. The larger of these is situated about 23 miles north of Butte near the small town of Basin and occurs as a quartz plug in granitic rock of the Boulder batholith (fig. 7) (Chelini 1966). About 400,000 short tons were reported to have been produced from this deposit between 1962 and 1974 (Burlington Northern, 1972). Quartz was also mined from the Snow White deposit about 30 miles northwest of Butte. This deposit is a quartzite of either Paleozoic or Precambrian age. Quartz from both of these deposits was shipped to plants in Washington but transportation costs have prevented the development of other high-purity quartz deposits in western Montana. Quartz deposits also occur in the Belt Supergroup northwest of Missoula (Burlington Northern, 1972). Most of these have not been evaluated by drilling.

Quartzose sandstone of the Pennsylvian-age Quadrant Formation in southwestern Montana has been investigated as a possible source of glass sand. As with quartz for metallurgical markets, transportation costs have prevented its development.

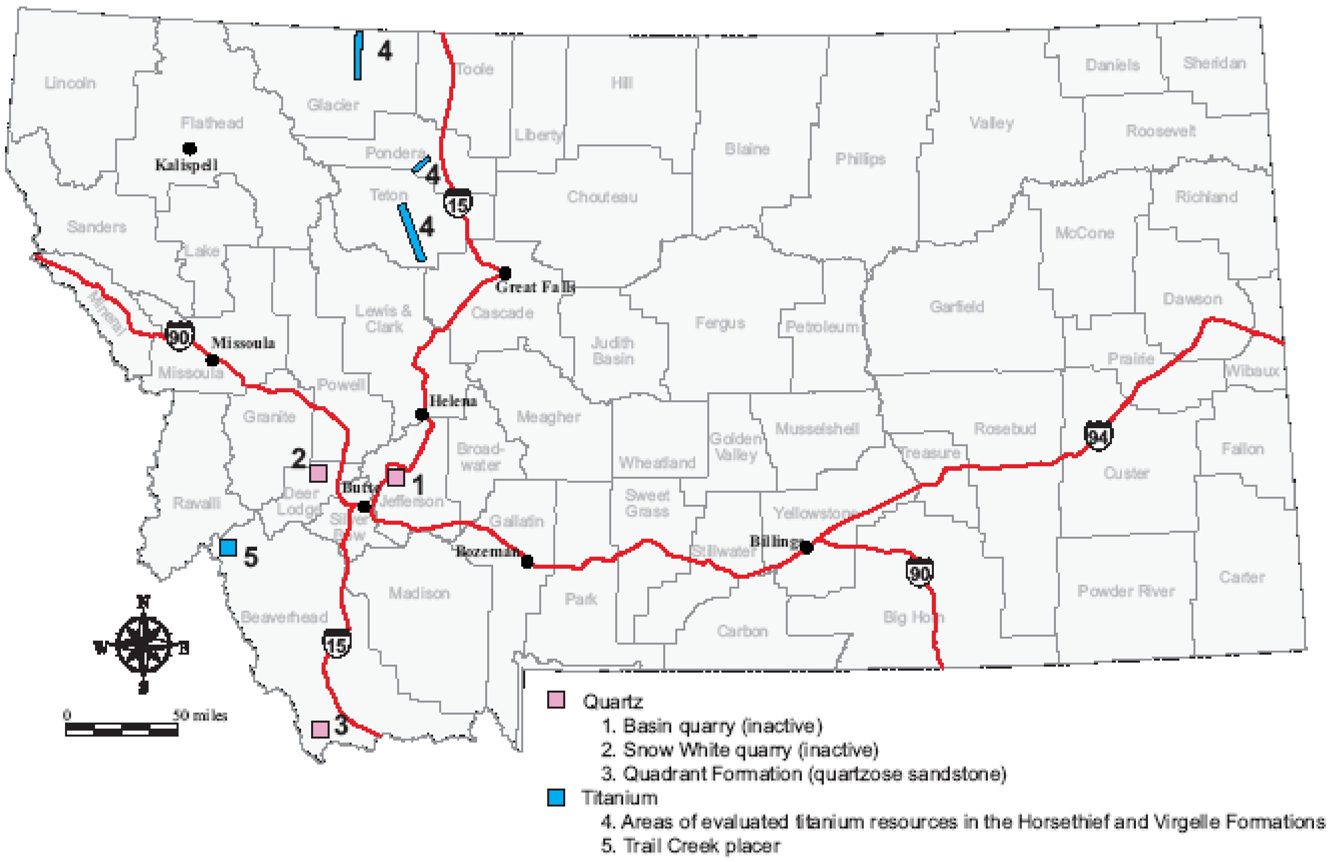

Figure 7. Quartz and titanium.

SAND AND GRAVEL

Sand and gravel deposits are generally extensive throughout the state, but because of differing source rocks, localized sorting, and concentration, the deposits have unpredictable values beyond local use (Knechtel and others, 1948). Those deposits that are derived from quartzite of the Belt Supergroup or silicified igneous rocks may be suitable for concrete aggregate. However, gravel deposits that contain argillite from the Belt Supergroup or Tertiary volcanics, may be suitable only for low-grade fill material. In northeastern Montana, north of the Missouri River, there are well-sorted gravels located above any modern flood plain. Some of these gravels are cemented with calcite; most are composed of quartzite clasts. There are also some outwash deposits from the continental glaciers that advanced into Montana. These contain igneous and metamorphic rock clasts and are not as well sorted nor are they of as good quality as the other deposits. The rest of the state contains gravel that is locally derived, but the degree of sorting is dependent on the deposit and the quality and use is dependent on the source area and its lithology.

Within the area of the Proterozoic Belt Supergroup of western Montana gravels tend to be dominated by quartzite and igneous clasts and are suitable for most construction needs. Detailed testing is necessary to determine gravels that meet the criteria for structural concrete. Most of the major river systems contain quality gravels within the fluvial valley; and in some areas there are substantial resources in the alluvial fan deposits along the margins. Most western Montana cities have more than adequate gravel resources to meet their demand. Prices are consistently too low to justify transporting gravel much more than a few miles.

STONE

Crushed Stone

Because of the extensive deposits of sand and gravel, crushed stone use is limited to railroad ballast. Meridian Aggregates Company mined railroad ballast from two quarries, the Essex quarry and the McQuarrie Stone quarry, both in Belt Supergroup quartzites adjacent to the Burlington Santa Fe Railroad, with average production of 200,000 to 250,000 tons per year (fig. 8) (McCulloch, 1994). After legislation regarding health hazards of crystalline silica, insurance companies for the railroad were reluctant to provide coverage for workers operating in dust containing crystalline silica. The production from these quarries was replaced by Conda Mining Company at Pipestone (located east of Butte) where production of fine-grained diorite has been increasing from 200,000 short tons per year (McCulloch, 2001).

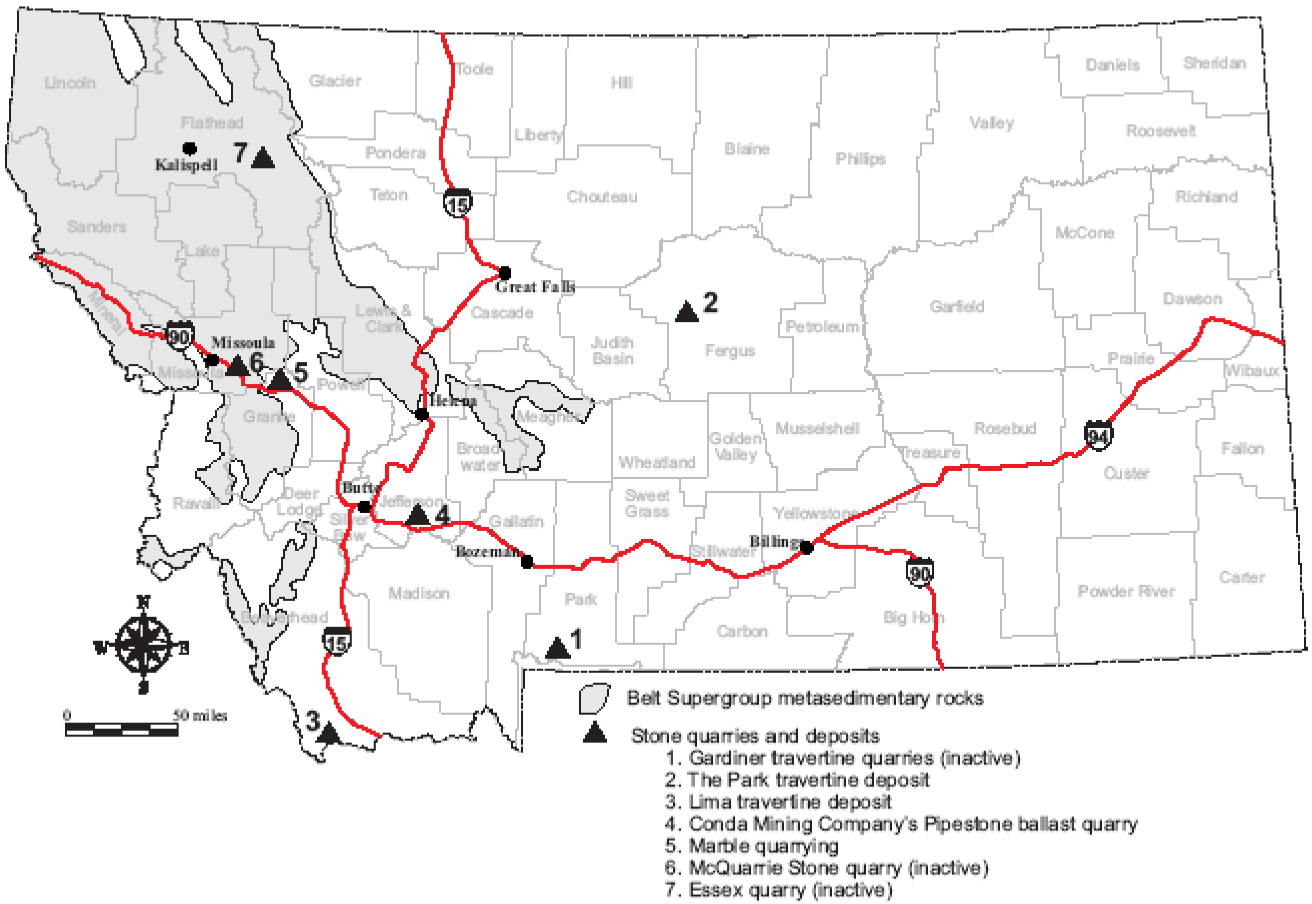

Figure 8. Exposoures of metasedimentary rocks of the Belt Supergroup modified from U.S. Geological Survey and Montana Bureau of Mines and Geology Special Publication 28 with stone quarries and deposits.

Decorative Stone

In common with many states, the stone industry of Montana has changed dramatically within the last 70 years or so from an industry dominated by granite quarries in the Butte and Helena areas that produced dimension stone to an industry that produces a variety of decorative stone. These include Montana "slate" and related metasedimentary stones, field stone, moss rock, and river rock of various lithologies. This is a highly fragmented industry with many small producers, particularly in northwestern Montana, supplying a limited number of stone yards. Because of the diversity of these stone products and their desirability in construction, much of this stone is shipped to major market areas such as the West Coast. In addition, some of the very expensive houses that are now being built in Montana are using substantial quantities of local stone, principally sandstone.

Belt Supergroup Stone

The older formations in the Belt Supergroup produce high-quality stone products for the building industry (fig. 8). The Pritchard Formation produces a number of products. The thinly bedded argillites are often separated by pyrite along some bedding planes. Because the pyrite is quite soluble during weathering, thin (1– to 2–inch) sheets of gray rock with orange, yellow, brown, and/or red surfaces can be easily separated. At some localities, sheets 3 feet by 4 feet are commonly quarried and even 6– to 10–foot sheets can be removed. Most deposits have abundant pieces in the 18-inch by 24-inch sizes. The market demand for facing stone has facilitated shipping as far as to Denver and Seattle. These stones are typically used indoors or in protected areas because they may further split during freeze-thaw conditions.

Where the beds are thicker, it is common to see polygonal stones from talus slopes sorted for sale. These "stackers" are commonly used in pillar supports, walls, and fireplace facing. The color ranges from gray-green to red-orange and thicknesses range from 3 inches to three feet. Quarrying from outcrop is facilitated by bedding that dips into the valley. Some of this stone is now being tumbled in trommels to develop a rounded form that seems to have a growing market. The Burke Formation at some localities yields a blue-gray quartzite in thin 1– to 2– inch beds. The locations of these deposits are most commonly found along the lower Flathead and Clark Fork Rivers in northwestern Montana and in the Libby to Kalispell area. Stone with slightly different textures and colors is produced from beds in the Belt Supergoup north of Helena.

The stone resource of the Belt Supergoup is large, but the availability is limited by access from existing roads and permitting from the land management agencies. Many of the argillite deposits have been depleted and many of the most accessible talus slopes have been hand picked. On Forest Service land these rocks are discretionary sales by the agency regardless of the value. Favorable strike and dip of the bedding with respect to topography and existing roads should be high on the prospecting priorities.

Landscape Boulders

For a number of years there has been a brisk demand for large boulders for landscaping. The Boulder batholith in the Butte – Helena area has supplied a large number of spherical to rounded gray multi-ton granite boulders. Gray, green, tan, and banded boulders up to several feet thick have been quarried from the thicker beds in the metasedimentary rocks of the Belt Supergroup. Mud cracks and ripple marks on bedding surfaces add to the attractiveness of this stone. Permian quartzites and shales have provided beautiful orange, red, and yellow boulders.

River Rock

Rounded cobbles are collected all over the western portion of the state for masonry uses. The most common collection areas are old placer workings and dredge tailings from past gold mining. At these localities the most marketable (about football-sized) rocks are washed and stacked. No permits are required to remove rocks from those sites. In southwestern Montana the placers contain both brightly and variably colored rocks that are derived from a variety of igneous sources and black and white-ribboned gneiss. The river rock business is comprised of small operators who collect and load stone onto pallets that are sold to stone yards. Much of the product ends up in west coast markets. There are far more resources than there are producers.

Field Stone

Field stone is quarried from Cretaceous sandstones in central Montana where is it either pried from outcrops or simply picked up from the fields, as the name implies. Lichen-encrusted stone (moss rock) is highly marketable.

Travertine

Travertine has been quarried since 1932 in the Gardiner area just north of Yellowstone National Park (fig. 8). These quarries are currently inactive and some are being reclaimed. A travertine deposit in central Montana about 12 miles north of Lewistown is six square miles in area (Berg, 1974). A smaller travertine deposit that covers at least two square miles is situated along the Idaho – Montana border. The Idaho portion of this deposit has been quarried for dimension stone by an Idaho producer.

Marble

Most of the commercial the marble deposits were formed by contact metamophism. The resulting deposits range from white to black with various other color combinations sporadically occurring. Early 20th century quarrying activities left a number of inactive quarry sites. Seasonal production occurs east of Missoula in the Garnet Mountains where blocks of the Silver Hill Formation are slabbed to produce countertops and tiles (fig. 8). The potential for successful quarrying appears to be limited because extensive deformation of the geologic units throughout western Montana resulted in multiple fractures and joint sets that limit the potential for large slabs. Marble deposits in Montana have been investigated as a source of crushed white marble for landscape rock and pulverized marble or ground calcium carbonate (GCC) for use as a functional filler. Although distant from markets, marble in southwestern Montana is a potential resource for these markets.

TALC

Montana leads the U.S. in both value and volume of talc produced. Rio Tinto Minerals mines talc at the Yellowstone Mine south of Ennis and Barretts Minerals, Inc. mines talc at the Treasure and Regal mines in the Dillon area (fig. 3). Talc mined in Montana has high purity and brightness values (GEB) generally in the 80s but also into the low 90s for some talc.

Markets for this talc include paper, paint, plastics, rubber, and specialty applications. Sierra Talc Company pioneered the use of talc in paper manufacture for pitch control in the 1950s. After several changes of ownership the talc mines formerly owned by the Sierra Talc Company, including the Yellowstone Mine, are now owned by Rio Tinto Minerals. Talc from the Yellowstone Mine is particularly well suited for pitch control because of its natural microcrystalline grain size. Talc is also used in paint formulations where it not only contributes desirable properties in the application of paint, but can also be substituted in part for extremely expensive TiO_2. In recent years, plastics have been a growth market for talc in general where talc is used as a functional filler because it increases the rigidity and improves other physical properties of polypropylene. The auto industry is a major consumer of plastics that incorporate talc as well as other functional fillers. Some talc used in these applications is surface modified with a chemical coating to improve the adhesion between the talc particle and resin.

The ceramic substrate for catalytic converters has become an important market for talc produced by Barretts Minerals from their Montana deposits. Essentially all of the ceramic substrates manufactured in the U. S. and Japan use Barretts' talc blended with kaolin; when fired the resulting ceramic has a low coefficient of thermal expansion.

Rio Tinto Minerals processes their Montana talc at two mills; one located at Three Forks and the other at the Sappington railroad siding and known as the Sappington Mill west of Three Forks (fig. 3). Barretts Minerals processes their talc at the Barretts mill situated south of Dillon. Talc ore from all mines is manually and mechanically sorted, pulverized in roller mills, hammer mills, and even in fluid energy mills to produce the very fine products. Barretts Minerals employs a ball mill followed by froth flotation in processing some of their talc ore. There can be significant variation in the physical and chemical properties of talc even from one deposit. This is both a blessing and a curse. Talc from a single deposit can satisfy the requirements of different markets, but this variation requires careful sorting, testing, and quality control. Talc deposits are by no means simple.

All of the talc deposits that have been mined in southwestern Montana occur in dolomitic marble of the Archean Wyoming Province (Berg, 1979). These hydrothermal deposits formed during a Proterozic retrograde event that followed the peak metamorphism of these rocks. A study in the Ruby Range (location of the Treasure and Regal mines) showed that silicon and magnesium were introduced by hydrothermal fluids and that calcium was removed to form talc (Anderson and others, 1990). Analyses of fluid inclusions in quartz associated with talc near the Yellowstone mine indicate a temperature of formation that ranged from 190^o to 250^o C and a pressure that corresponds to a depth of 3.5– to 14–km (Gammons and Matt, 2002). There is undoubtedly significant variation in the conditions of talc formation for the many different occurrences in southwestern Montana. Gammons and Matt (2002) hypothesize that the talc-forming solutions were related to Proterozoic rifting during formation of the Belt basin.

There are many occurrences of talc in southwestern Montana, some of which have been evaluated by drilling. Potential for additional mineable deposits exists, but the substantial amount of exploration for talc deposits in this part of Montana, makes it unlikely that large talc deposits such as those now being mined have been overlooked.

TITANIUM

Titanium occurs in two deposit types in Montana, paleoplacer and placer, both located east of the Continental Divide. Titaniferous magnetite deposits are found within the sandstones of the Cretaceous Virgelle and Horsethief Formations that form erosion-resistant cap rock on a series of buttes along the foothills of the eastern margin of the Rocky Mountains in north-central Montana (fig. 7). Cumulatively, they represent a resource of hundreds of millions of tons of ore. Lenticular titaniferous beds range in thickness from 2 to 20 ft and the larger deposits may contain from 2 to 51 million short tons of resources. The overburden over these deposits is generally less than 10 ft. Of the deposits tested, the titanium mineral is predominantly titaniferous magnetite with TiO_2 grades of 7–10 percent (Burlington Northern, 1970). West of the Continental Divide, placer deposits derived from intrusive rocks of the Idaho and Boulder batholiths have the best potential of all of the deposits sampled by the U.S. Bureau of Mines (Holt, 1964). The most significant of these is in the Trail Creek drainage near the Idaho border in southwestern Montana (fig. 7), where sampling revealed 18.1 to 71.8 percent ilmenite in the black sand concentrates. The host placers contained 0.8 to 9.6 lb of ilmenite per cubic yard.

VERMICULITE

A major source of vermiculite in the U.S. for many years was the Libby deposit in northwestern Montana (fig. 1). Vermiculite at this large deposit formed by the alteration of biotitite that is associated with an assemblage of alkalic igneous rocks. Mining of this deposit began in 1925 and continued until 1990 when mining ceased (Perry, 1948). Since closure the mill has been dismantled and the mine reclaimed. A declining market for insulation was cited as one reason for closure of the mine. However a major factor was undoubtedly the presence of asbestiform amphiboles in the ore. Shortly after closure legal actions were initiated in connection with health issues related to asbestiform minerals.

The Elk Gulch vermiculite deposit situated 65 miles south of Butte (fig. 1) has intermittently produced small quantities of vermiculite from biotite schist that has weathered to produce vermiculite (Berg, 1995). This biotite schist was formed at the contact between ultramafic bodies and the inclosing gneiss in this assemblage of Archean metamorphic rocks. Plans to develop this vermiculite deposit continue. Two other vermiculite deposits in southwestern Montana have had some drilling done on then. These are the Pony deposit and the Hamilton deposit from which there has been minor production (fig.1).

ZEOLITE

The common zeolite clinoptilolite occurs in both Tertiary and Cretaceous tuffaceous rocks in the intermontane basins of southwestern Montana (Berg and Cox, 2001). Clinoptilolite occurs at many localities, but typically in low concentration and zeolitization does not appear to be extensive. The largest recognized deposit is along Grasshopper Creek about 60 miles south of Butte where clinoptilolite is the dominant zeolite with lesser mordenite (fig. 3). The combined zeolite content (mordenite and clinoptilolite) in two areas along Grasshopper Creek was estimated to be approximately 70 percent with the remainder smectite, lithic fragments, quartz, glass, K feldspar, and calcite.

Based on a reconnaissance survey of tuffaceous rocks, it appears that Montana does not have the zeolite resources of many of the other western states.

Acknowledgments

Reviews by Mike Cerino, Edmond Deal, and John Metesh have improved this paper and are appreciated. Susan Smith of the Montana Bureau and Mines and Geology produced the maps. We also thank those many individuals who have shared information about industrial minerals with us, not just for this paper but over many years. We could not have written this paper without this information.

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Industrial Mineral Deposits of Colorado

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ABSTRACT

Colorado has a variety of economically important industrial mineral deposits ranging from sand and gravel to diamonds. In 2006, the total value of industrial mineral and construction material production in Colorado was $593 million.

Well over half of Colorado's industrial mineral production value comes from the sale of aggregate. Much of Colorado's aggregate is derived from alluvial sand and gravel deposits; however, crushed stone derived from Precambrian igneous and metamorphic rocks, Paleozoic to Mesozoic sedimentary rocks, and Tertiary volcanic rocks are important aggregate resources. Alluvial and eolian sands are quarried in the Colorado Springs area for industrial sand purposes. Dimension and decorative stone are quarried from several locations, which include various rock types: granite, red sandstone, alabaster, volcanic rocks, and the famous Yule Marble.

Limestone and shale from Cretaceous-age formations is mined in three localities along the densely populated Front Range for cement production. Nahcolite (sodium bicarbonate) is mined by an in situ solution process in the Piceance Basin of northwestern Colorado. Clay mined in Colorado is used mostly for the manufacture of bricks and tile and is derived from Cretaceous age formations. Gypsum is quarried from Pennsylvanian age evaporite deposits near the town of Gypsum in central Colorado and the Permian Lykins Formation in the Front Range.

High quality aquamarines are still being found in Colorado; however the Sweet Home rhodochrosite mine and the Kelsey Lake diamond mine are both shut down. Exploration for diamonds is continuing within the State Line kimberlite district.

INTRODUCTION

Industrial minerals and construction materials form an important part of the Colorado mineral and energy industry and have done so since the gold rush days starting in 1859. Fire clays were being mined in the early 1860s in the Golden area to manufacture ceramic products for use in the gold and silver camps of the Central City district (U.S. Geological Survey, 1964). Less valuable clays were used to make bricks. Sand and gravel, limestone, and possibly crushed stone were being used in the Front Range area as construction materials for buildings and roads. In South Park, south of the town of Fairplay, Park County, Native Americans acquired salt from a series of cold saline springs. In 1861, European pioneers "discovered" this site and began commercial production of salt. Native Americans also "mined" the multi-colored clays of the Dawson Formation in the area around Calhan west of Colorado Springs to make clay vessels and ceremonial body paint.

Through the intervening years these not-so-glamorous minerals have played an important and indispensable role in the development of the modern Colorado economy. The value of industrial minerals and construction materials in Colorado has increased substantially in recent years, and in 2006, the value of Colorado's industrial mineral production reached an all time high of $593 million, up 3 percent from the 2005 value of $577 million (fig. 1).

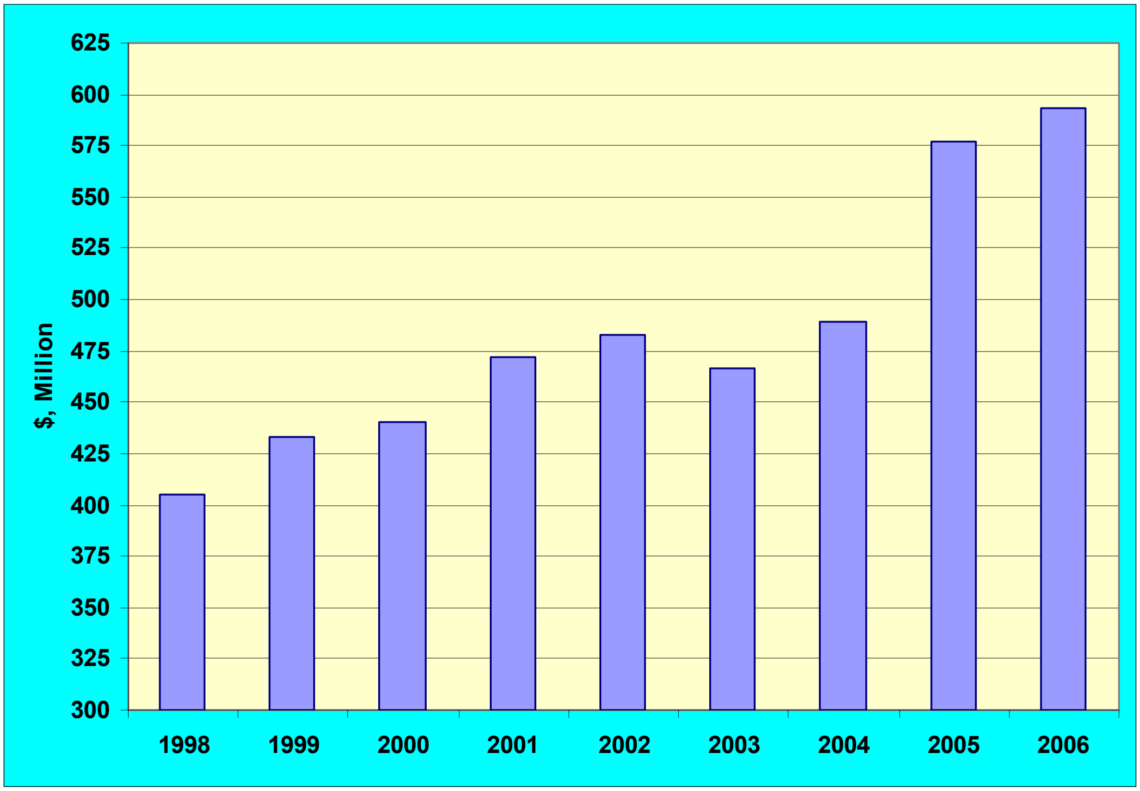

Figure 1. Value of Colorado industrial mineral and construction material production, 1998-2006.

CONSTRUCTION MATERIALS

Sand and Gravel

Sand and gravel deposits are unconsolidated deposits of sand- and gravel-sized material formed by the physical degradation of bedrock units by the agents of weathering. In Colorado, these agents include freeze-thaw cycles, stream abrasion, and wind erosion. Young sand and gravel deposits are found along most modern stream and river courses; older deposits are found in elevated or high–level terrace deposits left by ancient streams. The quality of sand and gravel deposits is determined by the soundness of the rock and mineral fragments and the grain size distribution. Igneous and metamorphic rock source areas generally provide hard, competent (or sound) clasts that maintain a wide size distribution. Sedimentary terrains generally produce softer, less-competent clasts that readily erode into smaller clasts with a smaller clast size distribution. In the modern streams draining Colorado's mountains, grain size decreases with increasing distances from the mountains; hence better sand and gravel deposits are found close to the many mountain ranges (fig. 2).

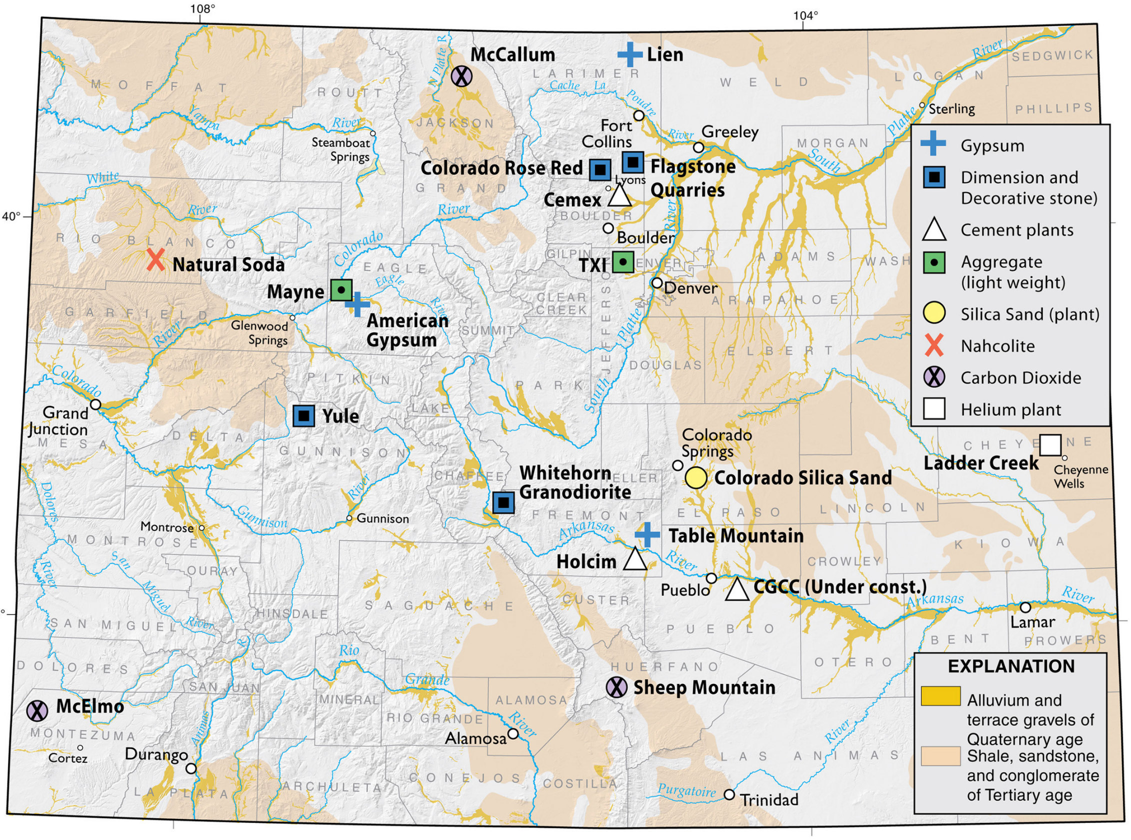

Figure 2. Map of Colorado showing distribution of sand and gravel deposits and industrial mineral deposits mentioned in the text.

Most of Colorado's current production of aggregate comes from sand and gravel deposits located along the state's many rivers and streams. About one-third of Colorado's annual aggregate production is from crushed stone quarries. In 2006, the annual production of sand and gravel was 48.6 million tons and 14.7 million tons of crushed stone. Production of sand and gravel and crushed stone has increased over the past several years (fig. 3); however, the unit value for sand and gravel is somewhat lower than that of crushed stone (fig. 4). Most aggregate quarries provide basic materials for the construction industry; however, some material is used for decorative stone (fig. 5).

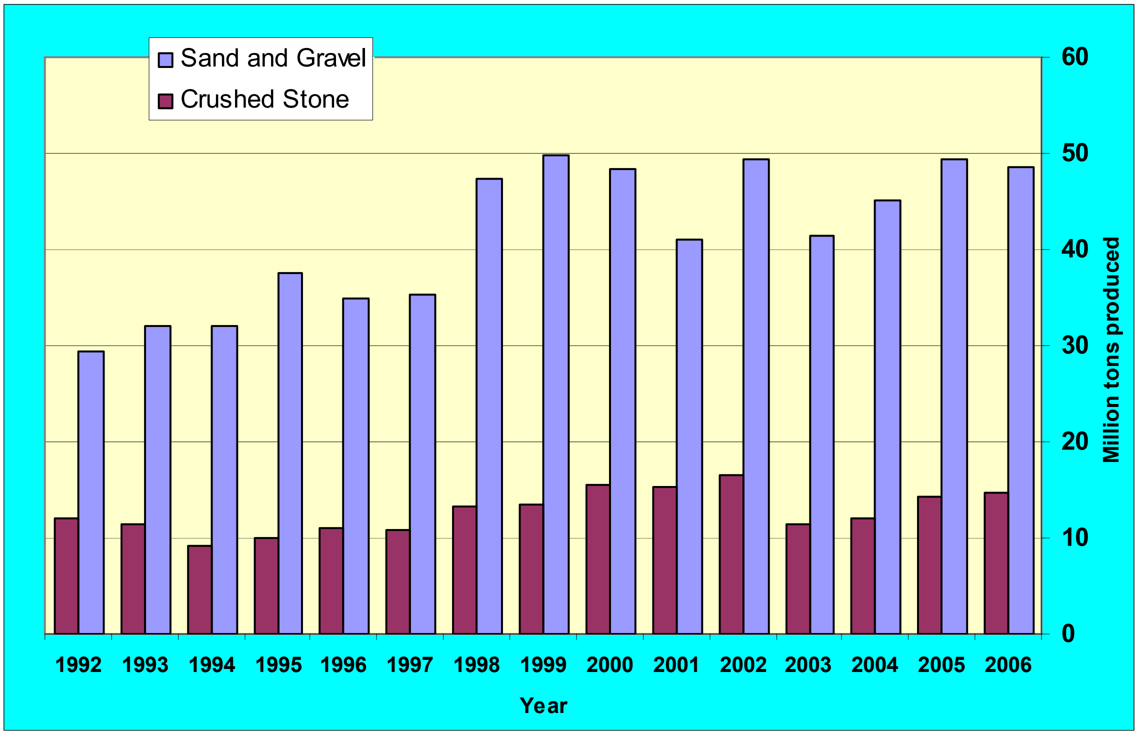

Figure 3. Production of sand and gravel versus crushed stone in Colorado, 1992-2006.

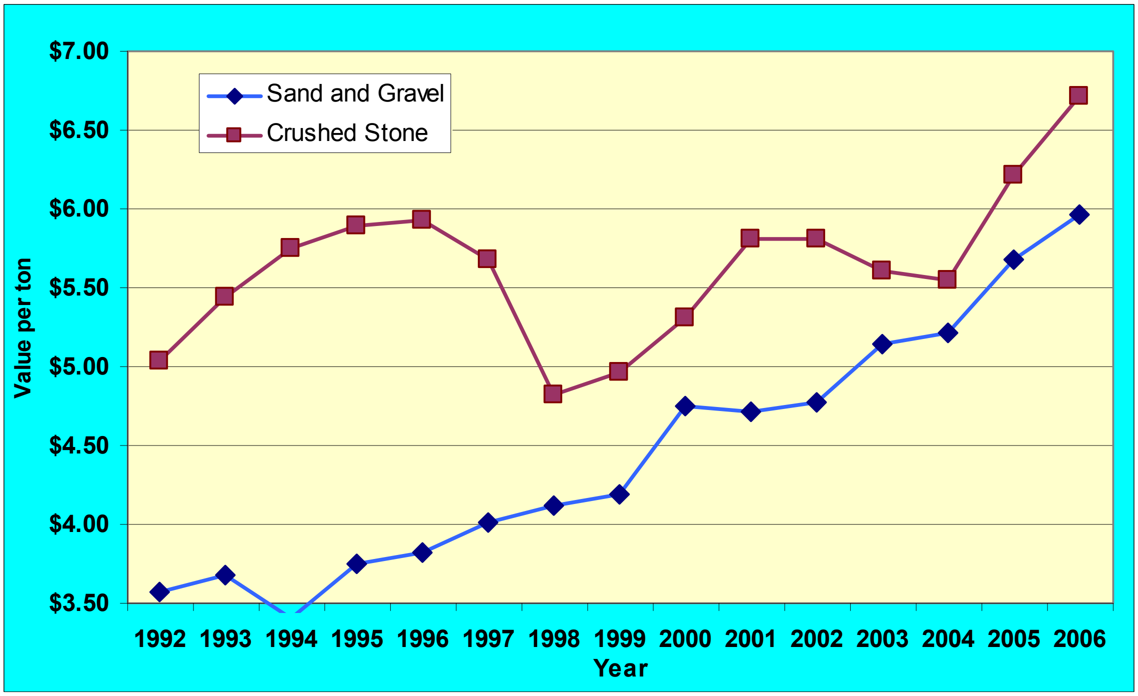

Figure 4. Unit value of sand and gravel versus crushed stone in Colorado, 1992-2006.

Figure 5. Sorted gravel to be used for decorative stone.

Crushed Stone

The diverse geology of the Rocky Mountains offers plenty of opportunity for crushed stone quarries in a variety of rock types including limestone, sandstone, intrusive and extrusive igneous rocks, and metamorphic rocks. Crushed stone quarries are found primarily along the highly populated Front Range corridor. Although much of the land in this area is underlain by high quality sand and gravel deposits, this resource has been "sterilized" by residential and ancillary development. Crushed stone quarries often produce material clasts that are particularly resistant to degradation, such as the 65 Ma shoshonitic andesite at Asphalt Paving Company's Ralston Quarry north of Golden. The andesite, which is quarried from an intrusive dike complex, was selected in the early 1990s to provide some of the base material for the runways, taxiways, and aprons at the new Denver International Airport.

At some localities in the Front Range, the upper Cretaceous Dakota Sandstone is comprised of quartz grains with abundant and durable silica cement, which makes the rock especially hard. It is quarried as rip-rap and decorative stone at the Table Mountain Quarry between Colorado Springs and Florence (fig. 6).

Aggregate Industries' Lyons Quarry southwest of Lyons produces crushed stone and large decorative blocks from a 62.5 ±3 Ma porphyritic dacite sill (Braddock and others, 1988). The impressive columnar jointing in the dacite allows for the removal of large blocks, which because of their decorative value, command high prices (fig. 7). The dacite is intruded into the red conglomerates, sandstones, and mudstones of the Pennsylvanian Fountain Formation, which are also quarried at this site.

Figure 6. Dakota Sandstone from Table Mountain Quarry, Fremont County.

Figure 7. Outcrop of Paleocene porphyritic dacite with well developed columnar jointing intruded into Pennsylvanian Fountain Formation, Lyons Quarry, Boulder County. Cliff face of the dacite is about 75 feet tall.

Dimension Stone

The Yule Marble Quarry in Gunnison County produces some of the finest white marble in the world. It is noted for its bright white color, delicate gray and gold veining, and ease of working (McGee, 1999). The Yule Marble is used in 30 buildings in Colorado and about 100 others throughout the U.S. Its first prominent use was in the floors and stairs of the Colorado State Capitol, which was constructed in 1895. Most notably, a single block of Yule Marble was used for the Tomb of the Unknowns at Arlington Cemetery and in the Lincoln Memorial in Washington, D.C. Most recently it was used as decorative facing, along with red Lyons Sandstone, in the main terminal building of Denver International Airport. In 2004, the Governor of Colorado, Bill Owens, declared the Yule Marble as the Colorado State Rock.

The Yule Marble Quarry began commercial production in 1905 and was closed just prior to World War II. It reopened in 1990, and in 2004, Polycor Inc., a Quebec based stone company, took control of the quarry. In 2005, Polycor produced about 60,000 cubic feet of marble (fig. 8, 9).

Figure 8. Interior of the Yule Marble Quarry, Gunnison County.

Figure 9. Spoil pile of blocks of Yule Marble in Yule Creek, Gunnison County.

The Yule Marble was formed by metamorphism of the Mississippian-age Leadville Limestone. A 12.4 ± 0.6 Ma (Mutschler and others, 1981) granite porphyry and quartz monzonite porphyry are exposed in the nearby Treasure Mountain Dome and the Raspberry Creek phacolith; these porphyries were responsible for the metamorphism of the limestone.

The Permian-age Lyons Sandstone is exposed along the northern Front Range foothills and is quarried extensively for flagstone, facing, and construction material. Its striking red color and fissility make it highly desirable and allow for ease of manufacture.

The stones are quarried mostly by hand and are cut and shaped on site (fig. 10, 11).


Figure 10. Hand trimming a piece of Lyons Sandstone at the Hotchkiss Sandstone Quarry, Larimer County.


Figure 11. Cross-bedded Lyons Sandstone, Hotchkiss Sandstone Quarry, Larimer County.

Colorado Rose Red Company quarries the 1,400 Ma Silver Plume Granite in Larimer County. The company uses a unique high pressure water jet method to cut the blocks from the underground quarry (fig. 12) and they face and polish the blocks using traditional methods.

Figure 12. Water jet cutter at Colorado Rose Red Quarry, Larimer County.

Several other granite bodies throughout the state have been quarried over the years but most are now dormant or mined only intermittently for decorative stone. The Aberdeen Gray Granite in Gunnison County is worthy of mention as it was used to construct the exterior of the Colorado State Capitol in Denver. The Whitehorn Granodiorite, located east of Salida in Chaffee County, is a Cretaceous-age intrusive stock that is very hard and has a striking blue color and was quarried for dimension stone in the first half of the Twentieth Century. Other quarried granites include the Precambrian granite from Cotopaxi and the granite of the Pikes Peak Batholith. Another noteworthy building stone is the grayish-pink, fine-grained rhyolite tuff of the distal facies of the Eocene-age Wall Mountain Tuff, which outcrops around the city of Castle Rock. This stone, locally known as the Castle Rock rhyolite, has a pleasing color and was used in the construction of the exterior of the Trinity Church in downtown Denver (Argall, 1949).

Gypsum

Gypsum has many uses as a construction material. The greatest use is in the fabrication of wallboard and as a setting retarder in portland cement. Gypsum is also sometimes used as a soil conditioner. Deposits of gypsum are widespread in Colorado. Bedded, white to pink gypsum is found in beds up to 90 feet thick in Jurassic to Permian-age rocks along the Front Range and Wet Mountain foothills belt. Many of these deposits have been worked in the past. Alabaster, a metamorphic equivalent of gypsum, is quarried today at the Owl Canyon Quarry in Larimer County. Thick beds of gypsum, anhydrite, and salt have also been encountered in deep oil and gas exploratory drill holes in eastern Colorado.

Massive gypsum beds and gypsum interstratified with shale and siltstones are found throughout the Eagle Basin in central Colorado. Exposures of the contorted and folded beds are well exposed along the Interstate 70 corridor from Eagle to Gypsum (fig 13). These Pennsylvanian-age evaporite deposits are as much as 4,700 feet thick. American Gypsum is currently exploiting these evaporites at their quarry just a few miles north of the town of Gypsum. American Gypsum uses pavement profilers (fig. 14), equipment designed originally to rip up highway pavement, to rip up the gypsum in the floor of the quarry; a loader picks up the ore and stores it in surge piles or loads the ore directly onto trucks for transport to their wallboard manufacturing plant in Gypsum.

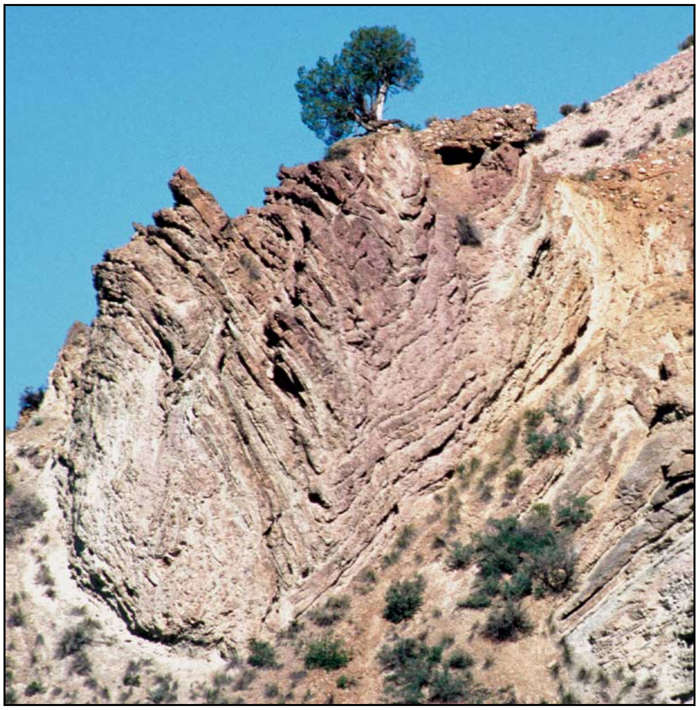

Figure 13. Syncline in Pennsylvanian Eagle Valley Evaporite, just north the town of Gypsum.

Figure 14. American Gypsum Quarry, Gypsum, Colorado. Pavement profiler is cutting furrows in the center of the photo. (Photo by John Keller)

In 2006, the American Gypsum Quarry produced 612,000 tons of gypsum. Approximately 600 million square feet of wallboard are manufactured annually at the plant. About 50 percent of the wallboard goes to the Colorado construction industry, and the remainder is marketed throughout the U.S. The company is in the process of developing a new mining area northeast of the current site. Over a span of a few years, mining will shift to the new site as reserves are depleted at the original site. The future mining area ensures that the wallboard plant can operate for at least another 20 years. The mine and plant employ approximately 125 people.

Colorado Lien, subsidiary of Pete Lien & Sons, Inc. of South Dakota, produces gypsum from the Munroe Quarry north of Fort Collins. Gypsum is extracted from the Permian Lykins Formation. Annual production averages about 50,000 tons. The majority of the material quarried is sold within the state to the cement industry.

Other gypsum-bearing rocks are found along the Arkansas River in Chaffee, Park, and Fremont counties in the Pennsylvanian-age Minturn Formation. Gypsum here ranges in color from white to light gray to brownish-yellow to black and is commonly 15 to 50 feet thick. Several small quarries operated in this area in the 1960s to 1970s.

Large resources of gypsum and anhydrite are found in the Pennsylvanian age Hermosa Formation in the Paradox Basin of western Colorado. The remote location and distance from markets has precluded significant development of these gypsum deposits.

Cement Rock

Portland cement is a complex compound that requires specific amounts of lime, silica, alumina, and iron oxide. Pure limestones generally require the addition of silica, alumina, and iron oxides. In Colorado, the limestones and argillaceous limestones of the Cretaceous-age Niobrara Formation generally contain the right chemical constituents in generally the right proportion for the manufacture of cement. The Niobrara Formation has been divided into several members. The lowermost member, the Fort Hays Limestone Member is composed of two cement-grade limestone units; the lower limestone contains about 85 percent $CaCO_3$, and the upper the upper argillaceous limestone contains 50 to 60 percent $CaCO_3$. Other members of the Niobrara Formation generally have higher percentages of pyrite making them undesirable for cement manufacture.

The main cement manufacturers in Colorado are Holcim (US) Inc. and CEMEX, Inc. The two companies produced a combined total of roughly 2.2 million tons of cement in 2006. Nationwide, cement consumption rose less than one percent in 2006 and is expected to continue rising in the upcoming years according to the Portland Cement Association. In Colorado, demand for cement will also increase because of our booming oil and gas industry. For example, recent legislation has increased well spacing in the Wattenberg field from 5 to 8 wells per 160 acres per producing formation. This could potentially result in the completion of an additional 24,000 wells or more. Tight cement supplies will make it difficult to keep pace with industry demand for new well completions.

The Portland Plant near Florence is operated by Holcim (US), Inc. (fig. 15). In 2006, the plant employed about 180 people and produced more than 1.8 million tons of cement. The majority of their product is used in the metropolitan Denver area and throughout Colorado, although some cement is also distributed to neighboring states such as New Mexico, Wyoming, Kansas, and Nebraska. Limestone from the Fort Hays Member is mined by Holcim as the principle raw ingredient for their cement. The Codell Sandstone, also of Cretaceous age, is mined for use as a silica additive. Most of the company's gypsum is imported from Oklahoma; some gypsum is produced as a byproduct of Holcim's lime calcining plant. Holcim is the second largest cement producer in the U.S.

Figure 15. Holcim cement plant and pit exposing the Fort Hays Limestone Member, Florence, Colorado. (Photo by John Keller)

Portland and masonry cement are produced at the Cemex, Inc. mine and processing plant near Lyons. The plant uses the dry processing method and employs about 100 people. Cement production in 2006 was 459,600 tons, most of which was utilized in the Front Range urban corridor. Cement ingredients (limestone and shale) are mined locally from the Niobrara Formation and the overlying Pierre Shale. Mexico-based Cemex purchased Britain-based RMC Group in March of 2005, making Cemex the world's largest supplier of ready mix concrete and third in cement production behind Lafarge and Holcim.

GCC Rio Grande, Inc., a subsidiary of Grupo Cementos de Chihuahua, has been planning and permitting a new cement plant in Pueblo during the past several years. Construction of the plant and mining facilities began in mid-2005 and is continuing at a good pace. The proposed mine and processing plant is expected to produce about one million tons of cement per year and will employ nearly 100 workers. The Fort Hays Member of the Niobrara Formation will be mined as the main cement ingredient. Gypsum, another ingredient of cement, will be mined locally as well.

Clay, Shale, and Lightweight Aggregate

The majority of the clay mined in Colorado is common clay, which is used mainly to make bricks and tiles or in the manufacture of cement and lightweight aggregate. Common clay is mined primarily in eastern Colorado, especially near the Front Range in Jefferson, Elbert, Douglas, El Paso, Pueblo, and Fremont counties. In 2006, Colorado clay mines produced an estimated 278,882 tons of clay valued at $1.6 million (fig. 16). In eastern Colorado, clay is mined principally from three formations: the Laramie Formation (Upper Cretaceous), the Dakota Sandstone (Lower Cretaceous), and the Dawson Formation (Upper Cretaceous to Tertiary). Elsewhere in the state, clay deposits within the Lykins, Morrison, Benton, Niobrara, Mesaverde and Vermejo Formations (ranging in age from Triassic to Cretaceous) have also been exploited.

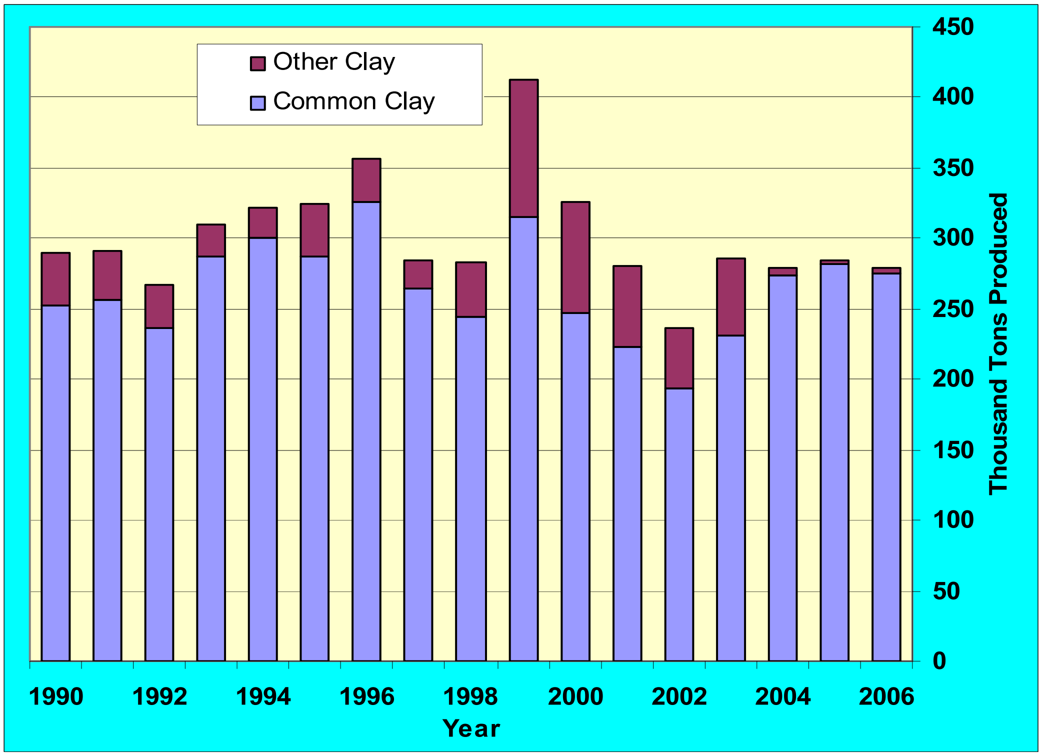

Figure 16. Total clay production in Colorado, 1990 to 2006. Most of the clay mined in Colorado is common clay, which is used primarily for making bricks. Other clays may include bentonite, refractory clay, or other specialty clays. 2006 figures are U.S. Geological Survey estimates.

Higher quality clays have also been produced from the Dakota and Dawson Formations. Both formations locally contain resources of refractory clay, which is used in the manufacture of refractory ware, such as crucibles and high-temperature firebricks for kilns. Current market demands have not warranted active mining of these deposits. Additionally, bentonite clay layers are found in altered volcanic ash in Fremont County, and locally in the Jurassic Morrison Formation and the Cretaceous Pierre Shale. Bentonite is frequently used as an absorbent (such as in kitty litter or to clean up hazardous fluid spills) and as a containment barrier (such as in clay liners for landfills). Colorado typically produces approximately 1,500 to 5,000 tons of bentonite annually.

Robinson Brick operates 14 clay mines in five Colorado counties including: Jefferson, Douglas, El Paso, Elbert, and Pueblo. These mines produce from the Dakota Formation, Benton Shale, Fox Hill Sandstone, Laramie Formation, and Dawson Formation – all of Cretaceous age. Robinson Brick produces approximately 180,000 tons of clay annually and employs about 600 people in one brick manufacturing plant, two block manufacturing plants, one stone quarry, and 19 showroom locations across the country in seven states: Colorado, Utah, Wyoming, Oklahoma, Nebraska, Illinois and Montana. There are also over 200 distributors of Robinson Brick Company products throughout the U.S. and Canada. Robinson Brick offers a full-size modular brick, as well as Old Brick Originals Thinbrick. All of the standard brick that is manufactured is FBX+ grade and is ISO 9001 registered. Old Brick Originals is real brick that is cut and packaged as Thinbrick veneer. Robinson Brick Company produces approximately 95 million bricks per year.

The Acme Brick Company mines approximately 110,000 tons of clay per year and, in 2006, manufactured 60 million bricks, most of which were sold outside of Colorado. Acme owns and operates five clay mines in Jefferson, Elbert, and Douglas counties: two mines produce clay from the Cretaceous Dakota Group, two produce from the lower Dawson (Denver) Formation (Paleocene), and one produces from the upper Dawson Formation (Eocene). Standard open-pit mining methods are utilized at all five mines.

Lakewood Brick owns and operates two clay pits, Doughty and Church, in northern Jefferson County. In 2006, they mined over 23,000 tons of clay from these two pits. Additionally, Lakewood Brick supplements its stockpiles with clay purchased from other local suppliers. At their brick processing facility, 37 employees manufacture an average of 17 million bricks per year. Half of this production remains in Colorado, while the remainder is exported to other states.

In 2006, 60,000 tons of clay were produced from ten Summit Brick Co. mines in El Paso, Fremont, and Pueblo counties. Approximately 27 million bricks are manufactured annually at the plant, about 35 percent of which are sold within Colorado and the remainder are shipped throughout the U.S. Raw clay costs average about $10 per ton delivered to the plant yard. The average price for face brick is about $325 per 1000 units. Summit's mines and plant employ approximately 85 people. One of the Summit mines produces common clay for brick manufacturing from the Cretaceous Pierre Shale. Three other mines produce fire clays from the Cretaceous Dakota Group, which are used to manufacture white brick. Summit's red-burning clays are derived from the Morrison Formation and from the contact zone between Precambrian Pikes Peak Granite and the Pennsylvanian Fountain Formation. Standard open-pit mining techniques are used at all the mines.

The Pierre Shale in northern Jefferson County is mined by TXI for use as lightweight aggregate. The raw shale is kiln-fired to the point where it expands in size and becomes low in density and weight (like popcorn). Lightweight aggregate is used in place of regular sand, gravel, or crushed stone in applications where excessive weight is undesirable, such as floors and walls in multi-story buildings. Cinder blocks are commonly made with lightweight aggregate. TXI employs 43 people at their mine and processing facility. In 2006, approximately 398,000 tons of shale were mined to produce 369,000 cubic yards of lightweight aggregate. Roughly, half of their finished product is sold within Colorado; the remainder is sold to other western states, particularly California.

Volcanic scoria from the 4,150 year old Dotsero crater is mined by the Mayne Block Company near the small town of Dotsero, Eagle County. Mayne uses the scoria as a lightweight aggregate in the fabrication of cinder blocks, landscaping material, and road cinders (Streufert and others, 1997).

INDUSTRIAL MINERALS

Industrial Sand

Production of industrial sand in Colorado is estimated to be over 70,000 tons based on average production values for the years 2004 and 2003. Colorado's leading industrial sand company is the Ohio-based Oglebay Norton Company. The local division office, Oglebay Norton Industrial Sands (ONIS), is located in Colorado Springs and supports 25 to 30 employees. ONIS markets "Colorado Silica Sand", a specialty industrial sand that is used primarily as filter media for water purification plants and as a construction material, largely for stucco. Some of their smaller markets include hydraulic fracturing material for oil and gas wells, gravel packs around water wells, and other applications where roundness, permeability, and strength are important parameters. Additionally, the sand is used as a landscaping material. The majority of product is exported outside of Colorado. Currently, ONIS extracts (essentially recycles) its silica sand from waste material cut from new developments in El Paso County where much of the surface cover is removed or scraped off before construction begins. The surface materials are generally Quaternary-age alluvial and/or eolian deposits consisting mostly of well-sorted and well-rounded grains of quartz.

Nahcolite (sodium bicarbonate)

Sodium bicarbonate from nahcolite is used in the manufacture of products such as food-grade baking soda, animal feed, cleaning products, pharmaceuticals, chemicals, water treatment, fire extinguishers, and paint blast media

Nahcolite ($NaHCO_3$) is found interbedded with halite and oil shale within the saline facies of the Parachute Creek Member of Eocene-age Green River Formation in the Piceance Basin of northwest Colorado. The nahcolite occurs as non bedded crystalline aggregates, laterally continuous units of fine-grained crystals disseminated in oil shale, brown microcrystalline beds, and white coarse-grained beds (Dyni, 1974). The thickness of the nahcolite bearing zones varies from 560 feet to over 900 feet with an average grade of nahcolite between 17 and 28 percent (Dyni, 1974). Beard and others (1974) estimated a total resource of 29 billion tons of nahcolite and 19 billion tons of dawsonite ($Na_3Al\ (CO_3)_3 \cdot 2Al\ (OH_3)$), containing 6.5 billion tons of alumina, within the Parachute Creek Member of the Green River Formation.

Natural Soda Inc. uses solution mining to recover sodium bicarbonate from nahcolite on its U.S. Bureau of Land Management (BLM) leases in the Piceance Basin in northwest Colorado. In 2006, the solution mine and recovery plant produced 98,739 tons of sodium bicarbonate. The facility has a production capacity of over 110,000 tons per year. Both food-grade (baking soda) and industrial-grade sodium bicarbonate products are produced at the plant (fig. 17).

Prices for sodium bicarbonate increased in 2005 in response to rising energy costs and other production costs. Chemical Market Reporter shows that the current market price for sodium bicarbonate varies from \$100 per ton (industrial grade) to \$200 per ton (USP food grade, coarse, bagged), with other grades in between. According to Linda Abolt, Quality Compliance Manager for Natural Soda's plant, "the average net back price enjoyed by sodium bicarbonate producers is approximately \$100 per ton". Using that as a rough guideline, the estimated value of Colorado's sodium bicarbonate production in 2006 was about \$10.9 million.

Figure 17. Aerial view of Natural Soda Inc's sodium bicarbonate plant in Rio Blanco County. Pipes that transport nahcolite-bearing solution from wells to the plant can be seen in the upper left. (Photo courtesy of Natural Soda, Inc.)

High-grade (>80 percent) nahcolite is recovered from the “Boise Bed” of the Green River Formation. Dissolution of the nahcolite is through drill holes along the base of the Boise Bed. The nahcolite-bearing solution is pumped to the surface via separate recovery wells (fig. 18). Natural Soda also owns the Rock School lease, an undeveloped nahcolite property nearby. The two properties, both leased from the BLM, together comprise over 9,500 acres in the Piceance Creek Basin. These leases contain in situ nahcolite resources estimated to exceed 4 billion tons.

American Soda, owned by Solvay Chemicals, Inc., produces sodium bicarbonate using soda ash feedstock from Solvay’s trona processing facility near Green River, Wyoming. The soda ash is railed to the American Soda plant in Parachute, Colorado. From 2001 to 2004, American Soda produced soda ash as well as sodium bicarbonate from nahcolite extracted from the Green River Formation in Rio Blanco County, Colorado. The company controls over 7,000 acres of nahcolite mineral leases in Rio Blanco County on land managed by the BLM.

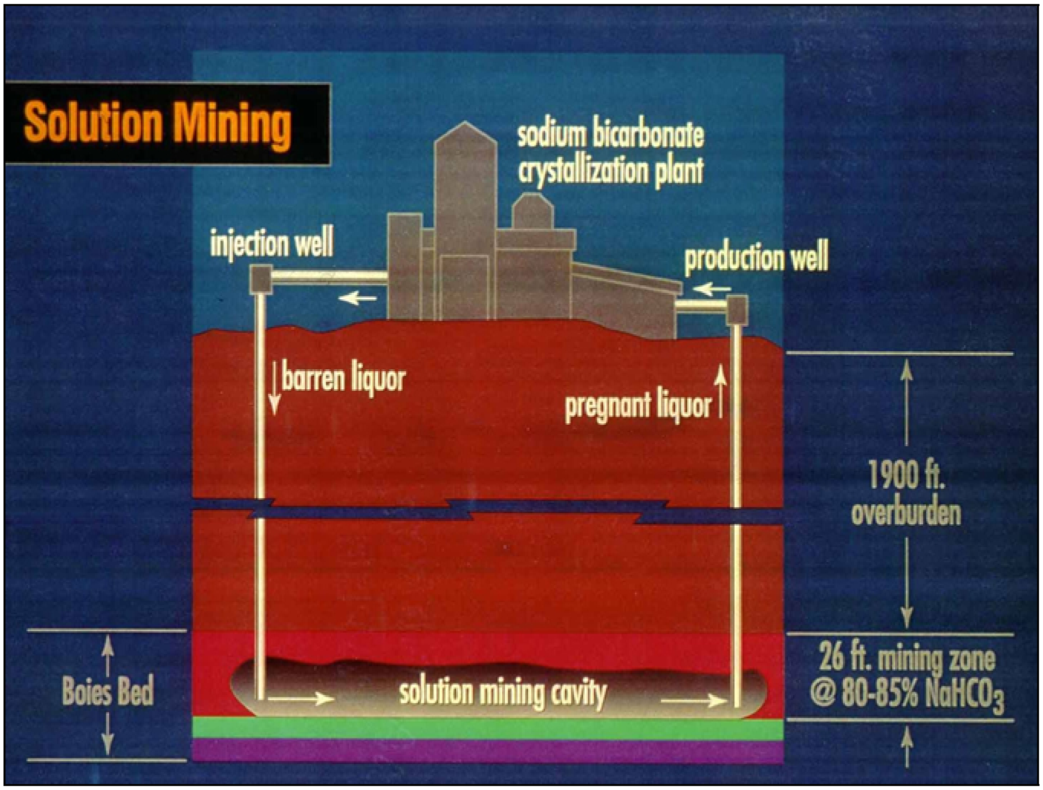

Figure 18. Schematic of Natural Soda's solution mining project, Rio Blanco County. Downloaded on 2/9/07 from http://www.naturalsoda.com/process.aspx.

Peat

Peat is a mixture of decomposed organic matter, the quality of which is determined by the level of decay. Sphagnum moss is the least decomposed and highest quality. Hypnum moss, reed-sedge, and humus are progressively more decomposed and of decreasing quality. Peat promotes plant growth and has widespread use as a soil additive in the agricultural and horticultural industries. It can also be used to filter or absorb contaminated water or hazardous material spills. There are three active permitted peat mines in Colorado, although only one of the mines is currently producing. This small, intermittent operation near Alamosa produces humus-grade peat to fill local landscaping needs. The peat is extracted from a dry bog as opposed to wetland areas typical of other worldwide peat resources. Colorado demand for peat is met primarily through imports, mostly from Canada.

GEM AND SPECIMEN MINERALS

Colorado is home to a large variety of gemstones and specimen-quality minerals. Some of these are produced by small commercial mining operations, and some are found by amateur collectors, or "rockhounds". Small commercial gem and mineral mining operations are typically owned and operated by truly dedicated and successful rockhounds.

According to preliminary U.S. Geological Survey estimates, the total reported value of 2006 gemstone production in Colorado was $358,000. The U.S. Geological Survey ranked Colorado as the 10th leading gemstone-producing state in 2005.

Colorado is renowned for several types of gemstones and specimen minerals. Table 1 lists a few of the better-known of these minerals. Figure 19 shows a fine specimen of rhodochrosite, the Colorado state mineral, from the Sweet Home Mine near Alma, Park County.

Table 1. Partial listing of gemstones and specimen-quality minerals found in Colorado.

Specimen mineral/gemstone name	Some Colorado occurrences.	Comments
Aquamarine	Mount Antero, Chaffee County	Colorado's official State Gemstone. Significant new discoveries on Mt. Antero recently. Found in cavities in the granite.
Rhodochrosite	Rhodochrosite is found in at least 17 counties in Colorado. The best-known locations include: Sweet Home Mine, Park County; Sunnyside Mine, San Juan County; Moose Mine, Gilpin County; Urad Mine, Clear Creek County.	Colorado's official State Mineral. The Sweet Home Mine produced the finest red transparent specimens in the world. The mine closed in 2004.
Diamond	State Line district, Larimer County	The Kelsey Lake diamond mine operated sporadically from the mid-1990s until 2002. It was the only commercial diamond mine in the U.S.
Amazonite	Crystal Peak area, Park and Teller Counties; Harris Park, Park County; Cameron Cone, Specimen Rock, and Crystal Park in El Paso County.	Spectacular blue-green feldspar occurs in miarolitic cavities in Pikes Peak Granite. Often found with smoky quartz.
Topaz	Devils Head, Douglas County; Spruce Grove campground area, Jefferson County; Crystal Park, El Paso County; Specimen Rock, El Paso County; Crystal Peak and Glen Cove areas, Teller County; Ruby Mountain, Chaffee County; Mt. Antero, Chaffee County.	Large quantities have been cut into gems and many others are on display around the world. Found in miarolitic cavities in granite or rhyolite.
Smoky quartz	Lake George and Florissant area, Park and Teller Counties; Devils Head, Douglas County; Harris Park, Park County; Wigwam Creek, Jefferson County; Specimen and Sentinal Rocks, Teller County.	Often found in association with amazonite in miarolitic cavities in Pikes Peak Granite.
Turquoise	Hall Mine near Villa Grove, Saguache County; Cripple Creek area, Teller County; King Mine, Conejos County; Turquoise Chief Mine, Lake County.	Colorado was at one time second only to Nevada in turquoise production. Currently being mined in the Cripple Creek area.
Lapis lazuli	Italian Mountain, Gunnison County	Italian Mountain is probably the best locality in North America for lapis. Lapis lazuli is a rock composed of several minerals. The main component is lazurite.
Peridot (gem-quality olivine)	Badger Creek area, Park and Fremont Counties.	This is a relatively recent discovery (1990s). Small pieces of gem-grade peridot are present in Tertiary-age basalt.

Figure 19. "Big Red": rhodochrosite (red) with quartz (gray) and tetrahedrite. This "plate" is about a foot in diameter. It was mined from Graham's Pocket in the Sweet Home Mine in Park County, Colorado. The mine stopped production in 2004. The specimen is owned and displayed by collector Keith Proctor. (Photo courtesy of Robert Spomer, Buena Vista Gem Works).

NON ENERGY GASES

Carbon Dioxide (CO2)

As one of several techniques for enhancing oil recovery, carbon dioxide (CO_2) flooding projects have been consistently and increasingly successful over the past 25 years. The number of CO_2 floods in the U.S. tripled in that time to over 70 in 2004 (Cappa and others, 2006). During this same period, CO_2 enhanced recovery production increased twenty fold, with most of the growth taking place in the 1980s prior to the 1986 price collapse. According to a recent *Oil & Gas Journal* survey of enhanced recovery projects, about four percent, or nearly 206,000 barrels per day, of U.S. oil production in 2004 came from CO_2 flood projects.

The Rangely Weber Sand miscible CO_2 flood in the northern Piceance Basin in northwestern Colorado is considered the third largest enhanced oil recovery (EOR) producing project worldwide and in the U.S. The Rangely project produces about 14,000 EOR barrels of oil per day. The most active CO_2 flooding area in the U.S. is the Permian Basin located in west Texas and eastern New Mexico. High-pressure pipelines supply CO_2 from natural source fields at Bravo Dome in northern New Mexico, and McElmo Dome and Sheep Mountain in southern Colorado. Shell's completion of the pipeline out of McElmo Dome in 1983 significantly increased the value of the naturally occurring CO_2 reserves in Colorado. In addition to EOR applications, CO_2 is used in welding gases, the manufacture of dry ice, and the food and beverage industry.

The largest natural CO_2 reserves are located at LaBarge-Big Piney Field in Wyoming (~55 trillion cubic feet (Tcf)), Bravo Dome in New Mexico (~16 Tcf), and McElmo Dome in

Colorado (~17 Tcf). Sheep Mountain in the northern Raton Basin in southeastern Colorado has an estimated 2.5 Tcf in ultimate CO_2 reserves. The CO_2 from McElmo and Sheep Mountain fields is very high quality; that is, 95 and 97 percent CO_2, respectively.

In 2006, the total production of CO_2 in Colorado was 373 billion cubic feet with a value of $291 million. About 96 percent of the CO_2 production comes from the Mississippian Leadville Limestone at the McElmo Dome field, which supplies CO_2 for EOR applications in the Permian Basin. Dike Mountain and Sheep Mountain fields in the northwestern part of the Raton Basin in Huerfano County produced approximately four percent of the state's total CO_2 in 2006. McCallum and McCallum South fields in the northeast part of the North Park Basin in Jackson County contributed less than one percent of the state's total carbon dioxide production in 2006.

Helium

Grade-A helium is produced at Duke Energy Field Service's Ladder Creek natural gas processing plant near Cheyenne Wells in eastern Colorado. The helium is liquefied at minus 458° F to separate it from the natural gas produced in the process. Helium is used for many purposes including medical imaging, welding, pressurizing and purging rockets, scientific and party balloons, fiber-optic cable production, production of metal alloys, and many others. The Ladder Creek plant produced 95.2 million cubic feet of Grade-A helium from local sources in 2005. The plant also produces helium from material that is trucked in from elsewhere. The U.S. Geological Survey estimates that the price range for privately produced Grade-A helium in 2005 is $67 to $73 per thousand cubic feet.

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Geology and Industrial Minerals of Oklahoma

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ABSTRACT

Oklahoma is best known for its energy resources, particularly oil and natural gas, and coal. One of the state's best kept secrets, however, is its nonfuel minerals production. Industrial minerals are produced in all 77 Oklahoma counties. The complex geology of the state is responsible for a wide variety of rock types, and therefore, account for myriad mineral resources. Major nonfuel mineral production is widespread, but it is concentrated in the Wichita, Arbuckle, and Ouachita mountains in the south and in the Ozark uplift in the northeast.

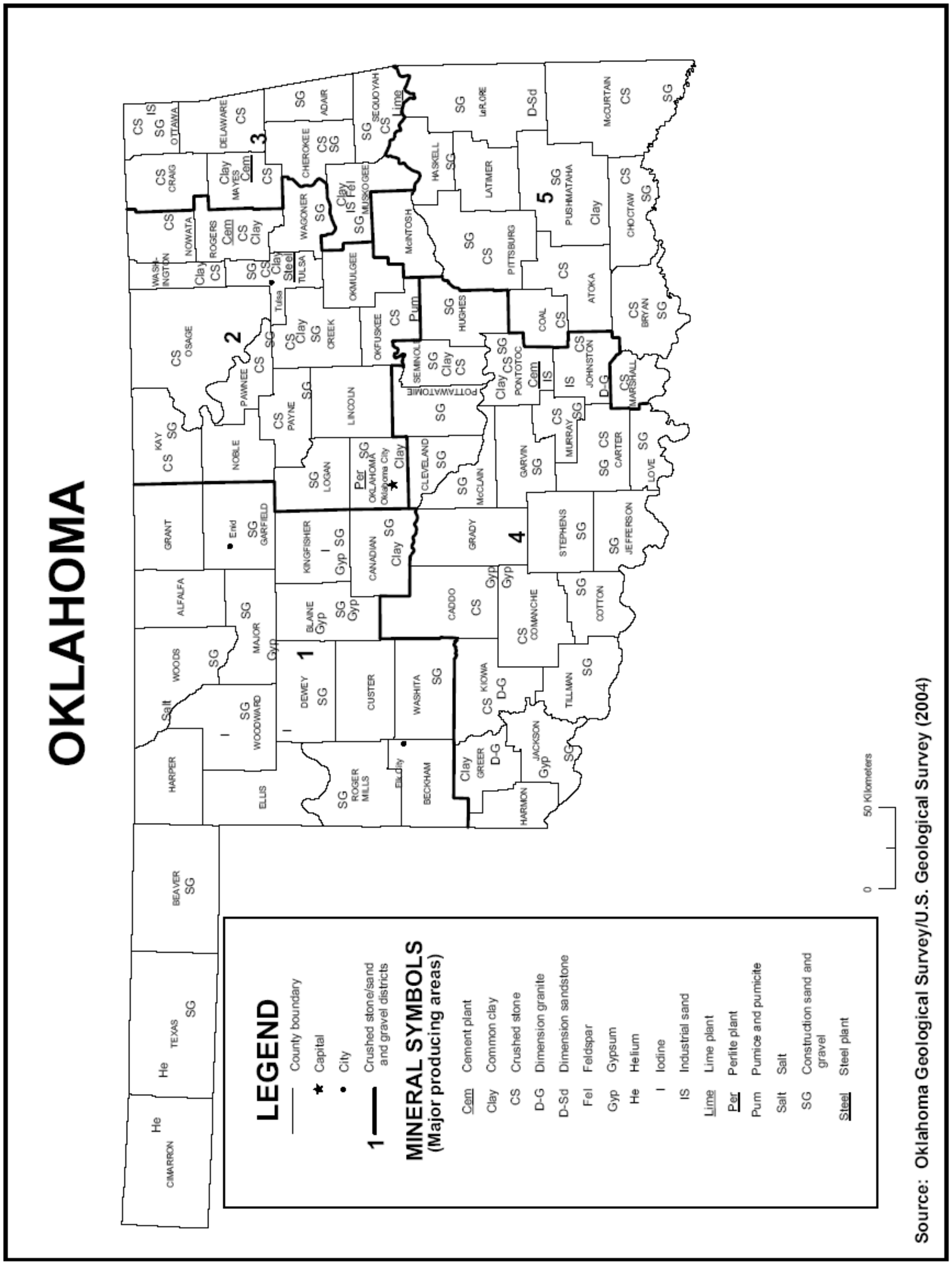
Presently, no metals are mined in Oklahoma, although lead and zinc production in the Picher–Miami field from underground mines in Oklahoma's northeast corner historically made important contributions to the state's economy until 1970. Copper was mined by open pit methods in southeastern Oklahoma before declining copper prices and increased production cost forced the operation to close in 1975. Almost all Oklahoma mines are open pit mines except for salt and iodine produced from brine wells; helium from natural gas wells; and one underground limestone mine.

Local and regional markets accounted for most industrial minerals produced in Indian Territory prior to statehood (1907). National markets became important throughout the twentieth century. Oklahoma raw nonfuel minerals had a value of $507 million in 2004, ranking first in the nation in gypsum and iodine production; second in tripoli; fourth in feldspar; seventh in common clays; and eighth in industrial sand and gravel. Other industrial minerals of significant value included crushed stone (limestone, dolomite, gypsum, sandstone, rhyolite, and granite) portland cement, construction sand and gravel, and masonry cement. Other significant production includes helium, salt, building stone, and volcanic ash.

INTRODUCTION

Oklahoma is a region of complex geology where several sedimentary basins are set amongst mountain ranges and uplifts. The state contains many classic areas where fundamental concepts of geology, petroleum exploration, and minerals production were formulated through the years. Because of its geologic history, Oklahoma has abundant mineral resources that include petroleum (crude oil and natural gas), coal, non-fuel minerals (lead, zinc, gypsum, limestone, sand and gravel), and water. The value of petroleum, coal, and non-fuel minerals reached a high of $11 billion in 1983, and was about $7 billion in 2005, making the minerals industry the greatest source of revenue in the state in recent years. Industrial nonfuel minerals production value was about $507 million in 2004.

Industrial minerals (which are the nonfuel, nonmetallic minerals with potential for economic use) are widely distributed in Oklahoma, and many are mined for local, regional, and national markets. Industrial mineral industries are active in all Oklahoma counties (fig. 1). Some of the most important regions producing industrial minerals are the Wichita, Arbuckle, and Ouachita Mountain uplifts in the south, and the Ozark uplift in the northeast; these areas, with some of the state's unique rock and mineral deposits, were uplifted and now are exposed at the land surface.



Source: Oklahoma Geological Survey/U.S. Geological Survey (2004)

Figure 1. Map of Oklahoma showing industrial minerals production by county. (U.S. Geological Survey, 2004).

Crushed-stone and building stone resources include limestone, dolomite, granite, and rhyolite; other major construction resources are cement (made from limestone and shale) and extensive sand and gravel deposits along modern and ancient rivers. Industrial sand (high-purity silica sand) is used for glassmaking, foundry sands, ceramics, and abrasives. Enormous resources of gypsum in western Oklahoma provide raw materials for wallboard, plaster, portland cement (as a retarder), and soil conditioners. Thick layers of rock salt underlie most of western Oklahoma, and natural springs emit high-salinity brine to the several salt plains. Oklahoma iodine, produced from deep brines in the northwest, is the nation's sole domestic supply. Other important industrial minerals in Oklahoma include clays and shales (to make brick and tile), tripoli, and volcanic ash (abrasives and/or absorbent materials).

The total estimated value of industrial mineral production in Oklahoma in 2004 was $507 million, and the state ranked 31st in the nation. Leading nonfuel commodities during 2004 were crushed stone ($195 million), sand and gravel ($53.7 million), industrial sand ($31.6 million), iodine ($15.9 million), and gypsum ($20.8 million). This report is a description of Oklahoma's industrial minerals arranged alphabetically. Many of the data are based upon reports by Johnson, 1969a, 1977, 1999), Morris (1982), and the Oklahoma Department of Mines (2004–2005); the reader is referred to these reports, as well as other reports that are referenced separately for several commodities.

GEOLOGY OF OKLAHOMA

The major geologic provinces of Oklahoma (fig. 2) include the following:

1) The cratonic and relatively stable northern shelf area, including the Ozark uplift;
2) The Ouachita geosyncline (Ouachita Mountain belt) and associated Arkoma Basin in the southeast; and,
3) The southern Oklahoma aulacogen (geosyncline), composed of the Anadarko, Ardmore, Marietta, and Hollis Basins as well as the Arbuckle and Wichita Mountain uplifts.

The Ouachita, Arbuckle, and Wichita fold belts originated from a series of Pennsylvanian orogenies in the Paleozoic geosynclines. The series of geosynclinal basins and uplifts of southern Oklahoma roughly forms an east-west boundary with the stable North American craton (shelf area) in the north.

Figure

Figure 2. Map of the major geological provinces of Oklahoma (Johnson, 1999).

Almost all the outcrops in Oklahoma are sedimentary rocks mostly of Paleozoic age (fig. 3). The remainder consists of igneous rocks of Precambrian age mainly in the Wichita and Arbuckle mountains; metamorphic rocks of Precambrian age in the eastern Arbuckles; and slightly metamorphosed sedimentary rocks in the Ouachita Mountains. Thicknesses of Paleozoic rocks range from 2,000 to 10,000 ft in the cratonic shelf, whereas the deep sedimentary basins in the south contain rock sequences from 30,000 to 40,000 ft thick (fig. 3). The sedimentary rocks overlie a basement composed of Precambrian to Middle Cambrian igneous rocks, and Precambrian metamorphic rocks and metasediments. The Upper Cambrian to Lower Mississippian strata are dominated by limestone and dolomite, and represent a period of crustal stability prior to Pennsylvanian orogenic activity. Thick shales and sandstones predominate from the Upper Mississippian through the Pennsylvanian. Red beds of shale and sandstone interbedded with gypsum, salt, and dolomite, characterize the Permian sediments. Triassic, Jurassic, and Tertiary rocks are mainly thin conglomerates, sandstones, and shales; Cretaceous rocks are similar but contain limestones.

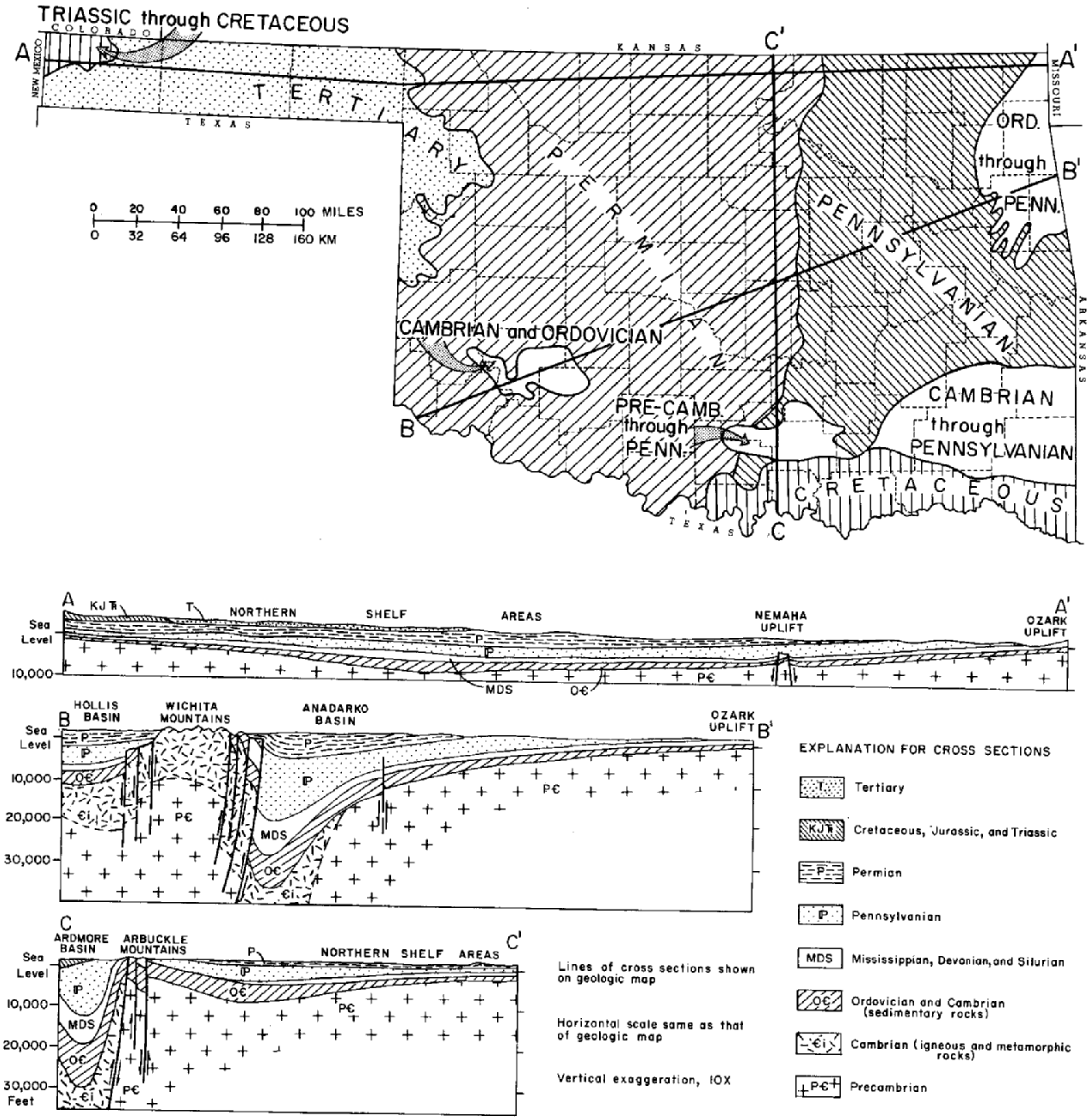


Figure 3. Map and cross sections of the generalized geology of Oklahoma (Johnson, 1999).

The Arbuckle Mountains in south-central Oklahoma is an area of low to moderate hills with 15,000 ft of folded and faulted, Late Cambrian to Pennsylvanian, sedimentary rocks. About 80 percent of these rocks are limestones and dolomites; the rest are shales and sandstones. During the Pennsylvanian, sedimentary rocks in the Arbuckles region were thrust upward and subsequently eroded. In the southeastern Arbuckles, this erosion created the largest exposure of Precambrian granites and gneisses in Oklahoma. The Arbuckles contain the largest variety of mineral resources in the state, all of which have been produced commercially: limestone, dolomite, industrial sand, granite, sand and gravel, shale, cement, iron ore, lead, zinc, asphalt, and oil and gas.

Middle Cambrian (and possibly Early Cambrian) igneous rocks, granite, rhyolite, and gabbro, are the major outcrops in the Wichita Mountains in southwestern Oklahoma. The foothills consist of scattered outcrops of limestones and dolomites that flank the igneous rock core. Several episodes of upward and northward thrusting during the Pennsylvanian built the

Wichitas, each followed by periods of erosion that removed the pre-Pennsylvanian sedimentary strata. Today the Wichitas consist of hills and peaks rising 500–1,000 ft above a Permian red-beds plain. Commercial mining operations produce granite, rhyolite, gabbro, limestone, dolomite, and sand and gravel. Oil and gas production takes place in the sedimentary rocks surrounding the Wichitas. Other uneconomic mineral prospects in the Wichitas include kaolin, montmorillonite, gold, silver, copper, lead, zinc, aluminum, titanium, and iron ores.

The Ouachita Mountains in southeastern Oklahoma and southwestern Arkansas form a series of high, arcuate, forested ridges and corresponding subparallel valleys. Thick units of Upper Cambrian through Lower Pennsylvanian sandstones and shales predominate, with lesser amounts of chert and novaculite, in a sequence exceeding 40,000 ft in total thickness. During the Pennsylvanian, folding and faulting of the sedimentary strata produced broad synclines and anticlines. Major thrust faulting also occurred at this time displacing strata northwestward up to 50 miles. Resistant sandstones form ridges with 500–1,500 ft of relief above valley floors formed in easily eroded shales. Minerals produced in the Ouachitas include limestone, quartzite, sand and gravel, asphaltite, copper, lead, and oil and gas.

Paleozoic outcrops outside the mountain regions are almost horizontal, commonly dipping 10–50 ft per mile. In eastern Oklahoma in the Ozark uplift, Paleozoic rocks are mostly Mississippian limestones and cherts. Elsewhere Pennsylvanian sandstones, limestones, and shales occur. In western Oklahoma, Permian red beds (shales and some sandstones) and evaporites (gypsum, anhydrite, and salt) are the predominate outcrops. The Paleozoic rocks typically form gently rolling hills and plains, but broad flat plains and valleys form where thick shales predominate. Resistant sandstones and limestones cap less resistant units to form buttes and cuestas up to 500 ft high. Badlands, sinkholes, and caves are common in gypsum-hill regions of western Oklahoma, and deeply dissected cavernous limestones and cherts are typical of the Ozark uplift. Paleozoic strata exposed at the surface in northeastern and central Oklahoma dip gently to the west, and elsewhere they dip towards basin axes. Paleozoic strata outside the mountain regions produce a very diverse group of mineral resources that include limestone, dolomite, sandstone, shale, gypsum, salt, dimension stone, sand and gravel, Tripoli, iodine, asphalt, chat, lead and zinc (Tri-State District), copper, coal, and oil and gas.

In southeastern Oklahoma, Cretaceous strata in the Gulf Coastal Plain are mostly loose sands, gravels, and limestones, and clays dipping gently southward. The landscape they form is gently rolling hills and plains, and only slightly dissected by streams. Minerals produced from the Cretaceous sediments are limestone and sand and gravel.

In the west, Tertiary deposits are loose sands, gravels, and clays that formed from streams draining the Rocky Mountains. This is the High Plains: a featureless, semiarid, flat upland surface. Minerals produced commercially from the Tertiary deposits include sand and gravel, clays, limestone (caliche), and leonardite (lignite).

Quaternary sediments, up to 100 ft thick, are mostly unconsolidated sand, silt, clay, and gravel deposited by streams, lakes, and wind during the Pleistocene and Holocene. Minerals mined in these deposits are sand and gravel, and volcanic ash deposited from volcanic eruptions that occurred in the western United States.

PETROLEUM RESOURCES

Oil and gas are a mixture of complex molecules of hydrogen and carbon formed from the decomposition of microscopic animals and plant material buried in muddy sediments of ancient seas that once covered Oklahoma. Deep burial of these muds created sufficient heat and pressure on the organic remains to transform them into oil and gas that could be squeezed out of the muds into more-porous sedimentary rocks, such as sandstone, limestone, and dolomite. Oil and gas therefore occupy the small spaces between grains or crystals that constitute a porous rock; they do not exist in large open cavities, or pools, as is sometimes believed, due to the use of the term "oil pool."

There is no reliable account of the first discovery of oil in the state, but Native Americans used oil and tar from natural seeps for medicinal purposes, and early settlers found oil springs in northeastern Oklahoma. A well drilled for salt near Salina, Mayes County, in 1859 accidentally struck oil, which was then sold for lamp oil. Although the first recorded production in the state was 30 barrels of oil in 1891, the first commercial oil well (one that makes a reasonable profit above the cost of drilling, equipping, and producing) was completed at Bartlesville, Washington County, in 1897. Since then, oil and/or gas production has been established in 74 of the 77 counties in the state.

Oklahoma has long been one of the main petroleum-producing states in the United States. Its reputation as an "oil state" was well established in the early 1900s by the discovery of such famous major oil fields as Glennpool, Cushing, Healdton, Sho–Vel–Tum, Burbank, Seminole, and Oklahoma City between 1905 and 1928. Early-day major gas fields discovered between 1912 and 1926 are the Red Oak–Norris, Guyman–Hugoton, and Kinta fields. Many more major oil and gags fields have been discovered through continued exploration of new frontiers since the late 1920s. Oklahoma was the leading producer of petroleum in the nation from 1907 through 1923; at present it is the fifth leading producer of oil, behind Texas, Alaska, Louisiana, and California, and is second in production of natural gas, behind Texas.

More than 500,000 wells have been drilled in Oklahoma in search of oil and gas, and about 120,000 of them are still producing. Total cumulative production from1891 through 2004 was about 14.6 billion barrels of oil and 92.3 trillion cubic feet of natural gas. The latest production figures show that Oklahoma produced 1.6 trillion cubic feet of natural gas during 2004 and 65 million barrels of oil in 2005.

Coal Resources

Vast resources of bituminous coal are present in an area of about 8,000 square miles of eastern Oklahoma. More than 200 million tons of coal were produced from hundreds of mines since coal mining began in 1873. In recent years, most coal mined in Oklahoma was used to generate electricity or to make coke for steelmaking. Oklahoma coal production reached a peak of about 57 million tons in 1981. Production was about 1.68 million tons in 2004.

Oklahoma coal beds are 0.8–10 ft thick, have 0.4–6.5 percent sulfur, and contain 11,500–14,500 British thermal units per pound. Early mining was mainly by underground methods, but since the 1950s almost all Oklahoma coal has been mined by surface methods. Surface mining is safer, recovers more coal, and is less costly on a per-ton basis. Current state regulations require restoration of the land after mining is completed. Surface mining, however, is restricted to shallow mining depths, where the coal beds are no more than 50–100 ft deep, so only a portion of coal resources can be recovered by surface methods.

NONFUEL MINERAL RESOURCES

Nonfuel minerals include both metals (lead, zinc, and copper) and nonmetals (limestone, gypsum, salt, clays, and sand and gravel). Oklahoma has an important history in metals production, although there is no mining of metallic resources at this time. Underground mining in the Miami–Picher field of northeastern Oklahoma yielded approximately 1.3 million tons of lead and 5.2 million tons of zinc between 1891 and 1970. Oklahoma led the United States in zinc production almost every year from 1918 through 1945. About 1.9 million tons of copper-shale ore were mined southwest of Altus, in Jackson County, between 1964 and 1975. Principal metallogenic provinces of Oklahoma are in the northeast corner of the state and in the Ouachita, Arbuckle, and Wichita mountains.

Nonmetallic minerals are widely distributed in Oklahoma (fig. 1), and many are mined for local, regional, and national markets. Crushed stone and building stone resources include limestone, dolomite, and granite deposits; other major construction resources are cement (made from limestone and shale) and extensive sand and gravel deposits along the modern and ancient river ways. Industrial sand (high-purity silica sand) present in the Arbuckle Mountains is used for glassmaking, foundry sands, ceramics, and abrasives. Enormous reserves of gypsum in the western part of the state are mined for wallboard, plaster, portland cement (as a retarder), and soil conditioners. Thick layers of rock salt underlie most of western Oklahoma at depths of 30–3,000 ft, and natural springs of salt water emit brine to the several salt plains in the region. Iodine is produced from deep oil-field brines (7,000–10,000 ft deep) by three companies in the Woodward–Vici–Dover area of northwestern Oklahoma. Oklahoma is the sole domestic producer of iodine. Other important nonmetallic minerals in Oklahoma include clays and shales (for brick and tile) and tripoli and volcanic ash (abrasive and/or absorbent materials).

Asphaltite

Asphaltite is a solid, dark-colored complex of hydrocarbons found in natural veins and deposits. Here it is considered a nonfuel-mineral resource, because in Oklahoma its use was mainly for road-surfacing and as a tar-like material. Asphaltite forms where crude oil migrated upward near the land surface: lighter hydrocarbons evaporated, leaving a thicker, heavy residue that impregnated rocks (rock asphalt), or that filled voids.

The major sources of rock asphalt and asphaltite are sedimentary rocks in and around the Arbuckle and Ouachita mountains of southern Oklahoma (Jordan, 1964). Additional smaller deposits occur in sedimentary rocks surrounding the Wichita Mountains and in northeast Oklahoma. Oklahoma produced about 3 million tons of asphalt between 1891 and 1960, chiefly from asphaltic sandstones and limestones in the Sulphur and Dougherty districts of the Arbuckle Mountains. Underground and surface mines produced asphaltite near Page, Sardis, and Jumbo in the Ouachita Mountains between 1890 and 1916.

Most rock asphalt mined in Oklahoma became paving material for roads in Oklahoma and adjacent states. Petroleum refineries now produce large quantities of the asphalt needed for road construction and maintenance. All natural rock asphalt quarries are currently inactive. Recently, however, there is renewed interest in natural asphaltite with several companies investigating the Oklahoma deposits, because of high oil prices. Asphaltite was used mainly in making roofing pitch, paints, varnishes, rubber substitutes, and electrical-wire insulation. Future demands for asphaltite and/or heavy oils can readily be satisfied by the vast resources that remain.

Cement

Raw materials for the manufacture of portland cement and masonry cement are limestone and clay or shale. Oklahoma has an abundance of both resources, and they are discussed separately elsewhere in this report. Historically, local demand, along with cheap, readily available energy resources was responsible for the growth of the cement industry in Oklahoma. Three plants currently manufacture cement in Mayes, Pontotoc, and Rogers counties: production quantity and value in 2004 was withheld to avoid disclosing company proprietary data.

Chat

Chat, which consists of crushed limestone, dolomite, and chert, was produced as a waste byproduct of mining and milling lead/zinc ores in the Tri-State district of northeastern Oklahoma. The material now exists in large stockpiles in the Miami–Picher area of Ottawa County. Its major use is as railroad ballast, highway construction, and concrete production. In 2005, Flint Rock Products, the sole hauler of chat, produced 468,947 tons (Oklahoma Department of Mines, 2004–2005).

Chemical Raw Materials

Oklahoma has vast resources of certain high-purity minerals suitable as raw materials for various chemical industries (Johnson, 1969b). Major deposits of limestone, dolomite, and industrial sand are in the south-central and eastern parts of the state, and gypsum and salt are widespread in the west; these individual resources are discussed elsewhere in this report. The abundance and purity of these minerals should enable manufacture of caustic soda, soda ash, chlorine, sulfur, sulfuric acid, lime, sodium silicate, and other chemical products. Oil, natural gas, and water, necessary for manufacturing these chemical products, are plentiful in most of Oklahoma, and bituminous coal is abundant in eastern Oklahoma.

Clay and Shale

Clay and shale occur in almost every county in Oklahoma. Deposits suitable for manufacturing red brick and tile products are widely distributed. A few localities have light-firing clays, low-grade refractory clays, and clays suitable for making stoneware and pottery. Clay suitable for making lightweight aggregate is common in the eastern portion of the state. Five brick plants operated by four companies in the state have the capacity to manufacture 450 million bricks per year.

The dominant clay mineral in most Oklahoma shale deposits is illite, which is associated with varying mixtures of clay-sized quartz and other clay minerals. Chlorite, kaolinite, montmorillonite, and mixed-layer clays generally are of lesser importance, although each may predominate in certain localities. Several types of specialty clays occur in parts of Oklahoma: small- to moderate-sized deposits of bentonite clay (montmorillonite) are associated with, and altered from, volcanic ash, mainly in northwestern Oklahoma. One company in Dewey County mines bentonite clays for absorbents. High oil prices and the consequential increase in oil and gas exploration drilling are the impetus recently for new exploration efforts to find bentonite clays in Oklahoma. Oil service companies that provide drilling fluid materials are searching for raw materials closer to oil-field drilling. Reports on clays and shales in Oklahoma are by Bellis (1972) and Johnson and others (1980). An excellent history of making brick in Oklahoma is by Robison (1980).

Shale is an important part of the construction industry in Oklahoma, even before statehood. More than 120 brick plants have operated since 1888; with most of them being in the central part of the state (Morris, 1982). Also, shale is one of the major ingredients at the three cement factories now operating in the state, and in 2004 the state produced an estimated 1.2 million metric tons of clay and shale (Oklahoma Department of Mines, 2004–2005). The U.S. Geological Survey reported that Oklahoma ranked seventh in the nation in common clay production (1.15 million metric tons valued at $2.41 million) (U.S. Geological Survey, 2004).

Dimension Stone

Dimension stone refers to stone that is finished to a specified dimension and/or shape. It is commonly quarried in rectangular blocks and sawed into slabs for additional finishing (usually a smooth surface or a high luster polish), and used in buildings monuments, furniture, industrial applications, and other uses. Other stone such as fieldstone, flagging, and rubble, is sold in its natural state, or it is broken into various shapes and sizes for use in building, paving, decorating, or other purposes (Mead and Austin, 2006).

Oklahoma has a variety of sandstones, limestones, dolomites, and granites suitable for building and ornamental purposes. Commercial and home construction uses native stone extensively in Oklahoma in recent years. The quality of some sandstone in eastern Oklahoma and oolitic limestone in southern Oklahoma compares favorably with any in the nation; several limestones and dolomites have unusual beauty and texture. Various types of dimension stone are discussed in this report under their rock names. In 2005, Oklahoma produced about 742,215 tons of dimension stone.

Dolomite

Large resources of high-purity Cambrian dolomite occur in the Arbuckle Mountains (Ham, 1949); it is quarried for high-purity material at one site and is quarried for crushed stone at two other sites in the Arbuckle Mountain region. The high-purity Royer Dolomite is about 500 ft thick in the area; other dolomite units are 400–500 ft thick. Smaller deposits or thinner beds, generally of lower purity, are known in the Wichita Mountains, in Delaware and Osage counties, and in widely scattered Permian outcrops of western Oklahoma; several of these deposits produce dimension stone and/or crushed stone.

Current and potential uses of dolomite are for fluxing stone, glass manufacture, refractories, dolomitic lime, magnesium metal, fertilizers, animal feed, and as a soil amendment. Quantity and value of current production are included within the estimates for crushed and dimension stone.

Granite

Granite and similar rocks of the Wichita and Arbuckle mountains of southern Oklahoma are extensively produced as dimension stone for the monument and building trades; crushed granite and rhyolite are produced mainly for railroad ballast (stone in the railroad bed), and intermittently for aggregate and rip-rap. In 2006, a brick company tested Wichita-Mountains granite for use as grog in the manufacture of bricks. Granite and similar rocks in Oklahoma are Precambrian and Cambrian in age. Colors are red, pink, gray, and black, and textures range from finely to coarsely crystalline.

At present, quarries in Greer, Kiowa, Johnston, and Murray counties regularly produce granite and rhyolite, and in 2005 Oklahoma produced about 4.81 million short tons of granite and rhyolite (Oklahoma Department of Mines, 2004–2005). The vast majority of granite and rhyolite production (4.78 million tons) was quarried for railroad ballast. The value of granite and rhyolite production includes other categories (dimension stone and crushed stone).

Gypsum

Enormous resources of high-purity gypsum occur in western Oklahoma. Blaine Formation gypsum in northwest and southwest Oklahoma ranges from 5 to 30 ft thick, and is 95–99 percent pure. The Cloud Chief gypsum of Washita and Caddo counties ranges between 25 and 100 ft thick, and is 92–97 percent pure. Anhydrite outcrops occur only locally, but it is present underground where overburden is between 25 and 100 ft and more.

Total gypsum resources in Oklahoma are estimated at 48 billion short tons. Because the gypsum beds typically forms hills in the semiarid climate of western Oklahoma, and because gypsum layers are nearly flat lying, without folds or faults, the gypsum resources are best suited for open-pit mining methods (Johnson, 1978).

Oklahoma ranks first in the U.S. in gypsum production, with about 4.7 million metric tons produced in 2005 (Oklahoma Department of Mines, 2004–2005). The production of crude gypsum in Oklahoma in 2004 was 3.25 million metric tons valued at $20.8 million (U.S. Geological Survey, 2004). Present uses are as plaster for interior walls and wallboard, special plasters for medical and other uses, retarders in portland cement manufacture, fillers, and soil conditioner.

Helium

Helium is a colorless, odorless, and nonpoisonous gas, and is the second lightest of all elements. One gas plant near Keyes, in Cimarron County, extracts helium from natural gas from the Hugoton gas field. Managed by the U.S. Bureau of Land Management, the helium-producing plants were privatized over the last decade or so. The major uses of helium include cryogenic applications, pressurizing and purging, welding cover gas, controlled atmospheres, leak detection, breathing mixtures, and others.

During the Cold War, helium was a strategic mineral. Its role as a purging agent for rockets and jet engines was crucial to the U.S. Department of Defense. For these reasons, the U.S. Government controlled the production and sale of helium. When the Cold War ended, helium lost its strategic importance and the production and sale became privatized.

Industrial Sand

Two operations (Johnston and Pontotoc counties) in the Arbuckle Mountains region mine large deposits of high-purity silica sand (Ordovician Simpson Group), with plant-run sands containing 99.8 percent silica and normally only 0.01–0.03 percent iron oxide (Ham, 1945). Ordovician sand almost as pure occurs in northeastern Oklahoma, and scattered exposures of Cretaceous sands with 98.5–99.5 percent silica occur south and east of the Arbuckles. Alluvial sand from the Arkansas River in Muskogee County produces feldspathic sand specially treated for glass manufacture: the processed sand includes about 75 percent quartz (silica), about 25 percent feldspar, and less than 0.04 percent iron oxide. In 2004, Oklahoma produced 1.39 million metric tons of industrial sand valued at $31.6 million (not including feldspar). Oklahoma ranks eighth in the U.S. in industrial sand production. Based on production of feldspathic sand from the Arkansas River, Oklahoma ranks fourth in the nation in feldspar production.

A number of glass manufacturing plants in Oklahoma and adjacent states manufacture glass products including container glass, flat glass, tumblers, tableware, and Pyrex® glass. Other products made from Oklahoma industrial sand are foundry sands, ceramics, and sodium silicate. One silica-sand plant produces ground silica flour for use in ceramics, abrasives, and inert filler.

Iodine

Iodine, a grayish-black, nonmetallic element, is solid at ordinary temperatures. In Oklahoma, it is dissolved in iodine-rich natural brines (300 ppm iodine) at a depth of 6,000–10,000 ft below the surface in the Woodward, Vici, and Dover areas in northwestern Oklahoma (Krukowski and Johnson, 2006). Major production comes from the Woodward and Vici areas, where iodine occurs in the Morrowan (basal Pennsylvanian) sandstones in a south-trending paleovalley called the Woodward "trench." Iodine production also comes from other Paleozoic rocks (sandstones, limestones, and dolomites) as a byproduct of oil and gas production. Wells drilled into these rocks produce iodine-rich brines, which are then treated chemically. Iodine is then precipitated after being stripped the brine. The waste brine is treated and re-injected into the same producing formation (Cotton, 1978). Oklahoma brines range from 100 to 1,560 ppm iodine, are 300–350 ppm iodine in most producing wells, and are the richest known iodine brines in the world (Krukowski and Johnson,2006).

Oklahoma's production of iodine began in 1977, and when iodine production in Michigan ceased in 1987, Oklahoma became the sole source of domestic iodine. The U.S. (Oklahoma) produces about 4.8 percent of the world's annual output (Lyday, 2007). Three companies operate three plants (one is a mini-plant) in northwest Oklahoma. Annual production is estimated at 1,220 metric tons valued at about $23 million (Lyday, 2007). Major uses of iodine include catalysts, stabilizers, radiopaques, animal feeds, disinfectants, pharmaceuticals, photography, and colorants.

Lime

Quicklime, made by calcining high-purity limestone at very high temperatures, has many chemical and industrial uses, as well as construction and agriculture applications. Lime is manufactured in Sequoyah County from high-calcium limestone of the Silurian St. Clair Limestone, mined by open-pit and underground methods. Additional deposits of high-purity limestone are present in northeastern, south-central, and southeastern Oklahoma.

Lime products include quicklime, hydrated lime, and lime slurry. Quicklime uses include steelmaking, flue gas desulphurization, soil stabilization in highway and building construction, manufacturing paper products, and sanitation and water treatment systems. Hydrated lime uses include municipal sanitation and water treatment, soil stabilization for highway and building construction, production of chemicals, and production of stuccos, plasters, and mortars. The major use of lime slurry is in soil stabilization for highway and building construction. Markets for Oklahoma lime are in Texas, Arkansas, Oklahoma, Colorado, and Louisiana. The amount of lime produced in Oklahoma and its value are withheld to protect the proprietary data of the manufacturer.

Limestone

Limestone is abundant in northeastern Oklahoma, in the Wichita and Arbuckle Mountain areas, and in south-eastern Oklahoma (Rowland, 1972). It is used mainly for concrete aggregate in highway and other construction projects, railroad ballast, glassmaking, the manufacture of cement, and the manufacture of chemical-grade lime. Other uses of limestone include dimension stone and pulverized limestone or ground calcium carbonate (GCC). Pulverized limestone is used to produce construction materials such as roofing shingles and asphalt paving, as an additive in animal feed, as a soil conditioner, for flue gas desulphurization, and for dust control in coal mining operations. In western and Panhandle districts, extensive caliche deposits substitute for some purposes.

In the Arbuckle and Wichita mountains, major limestone formations are several hundred to several thousand feet thick, their outcrops covering large areas. They are an almost unlimited resource of stone. The principal market for stone from these two areas is the Oklahoma City metropolitan area, and the Dallas–Fort Worth area in Texas. Usable limestones in the southeast, northeast, and north-central parts of the state commonly are 10–50 ft thick, providing stone for local markets.

In 2005, 54 companies quarried limestone throughout Oklahoma producing about in 45.2 million tons (Oklahoma Department of Mines, 2004–2005).

Salt

Thick sequences of Permian rock salt (NaCl) underlie most of western Oklahoma at depths ranging from 30 to more than 3,000 ft (Jordan and Vosburg, 1963). Individual salt beds are 5–25 ft thick and are interbedded with thinner layers of shale and anhydrite. The depth and thickness of salt beds in the region make them suitable for either underground or solution mining, but only solution mining of salt has taken place in Oklahoma. Underground salt mining in the same salt beds occurs in Kansas, however, just 60 miles north of the state line. Near Sayre, in Bekham County, solution mining of salt has occurred intermittently, and the products marketed either as high-salinity brines or precipitated crystal salt.

Major natural salt plains and springs occur along some rivers of western Oklahoma. Saturated brines that formed by dissolution of salt in the shallow subsurface, discharge at the surface at natural salt springs or salt plains, with emissions ranging from 150 to 3,000 tons of salt per day at each site. The natural springs commercially produced salt since the beginning of twentieth century, and even earlier by Native Americans. Several small salt producers tapped the salt plains in the northwest and southwest, each producing about 2,000–10,000 tons of solar salt per year in iron drying pens. Native Americans precipitated salt from the brines onto feathers or small branches for purposes of trade. Only one major producer operates a solar salt facility in Big Salt Plain near Freedom, in Woods County.

Oklahoma has vast salt resources estimated at 20 trillion tons, which are virtually untapped. Production from the one solar-salt plant in Woods County during 2005 was reported by the Oklahoma Department of Mines (2004–2005) as 78,782 tons. The salt was used primarily in recharging water softeners, for stockfeed, and road de-icing. Other potential uses include the chemicals industry (chlorine, caustic soda, soda ash, and sodium) and human consumption.

Sand and Gravel

Sand and gravel, essential for almost all types of construction, are widespread and available in most of Oklahoma. Principal deposits are along present-day major rivers, in terrace-like remnants of Pleistocene river beds, and in Tertiary deposits covering much of the northwest. Gravels are common in the western third of the state, in and around the Wichita and Arbuckle mountains, and in Cretaceous rocks south of the Arbuckle and Ouachita mountains.

Sand and gravel are used in the construction industry chiefly as aggregate, which is the term used for the inert and hard, fragmental material that is bound by a cementing material to form concrete, mortar, or plaster. The paving industry uses sand and gravel as aggregate in both asphalt and portland-cement concretes.

In 2005, the Oklahoma Department of Mines (2004–2005) reported that 192 companies operated sand and gravel pits in 57 of 77 counties in Oklahoma. Oklahoma Department of Mines reported that Oklahoma produced almost 24.0 million tons of construction sand and gravel in 2005. This figure includes industrial sand as well as some fill dirt production.

Sandstone

Sandstone is a common rock type in most parts of Oklahoma. Deposits in the eastern half of the state are mostly hard; are gray, brown, or buff; and some are suitable for dimension stone or aggregate. In the western half of the state, most sandstones are soft or friable; are reddish-brown; and are only locally suitable for building material. Several operators in east-central Oklahoma quarry sandstone as dimension stone. In the eastern half of the state at several places, operators quarry sandstone for riprap and aggregate.

Tripoli

Tripoli is a white or cream-colored, microcrystalline form of high-purity silica that is porous, lightweight, and friable. It is derived from a partly siliceous parent sedimentary rock from which soluble carbonate minerals have been leached (Quirk and Bates, 1978). Important tripoli deposits are present in northeastern Oklahoma; the first mine opened in the Missouri–Oklahoma tripoli district in 1869. Tripoli deposits typically are 2–20 ft thick and they occur in Mississippian-age cherty limestones beneath only 2–10 ft of overburden.

After stockpiling, the tripoli is dried, crushed, and screened to various grain sizes. Ground tripoli is used mainly as an additive in paints, as a mild abrasive or in buffing and polishing compounds. It is prized for its abrasiveness, resistance, porosity, permeability absorption, and low specific gravity. One company operated a number of pits during 2005 in Ottawa County. The U.S. Geological Survey (2004) reported that Oklahoma ranked second in tripoli production in the U.S., producing 32,100 metric tons valued at $2.12 million. The Oklahoma Department of Mines reported that Oklahoma produced 33,667 tons of tripoli in 2005.

Volcanic Ash

Small to large deposits of unconsolidated volcanic ash occur in western and east-central Oklahoma (Burwell and Ham, 1949). They are the result of local accumulations of airborne ash and dust that was blown from volcanoes erupting in New Mexico, Wyoming, and other western states during Tertiary and Pleistocene times. Some ash deposits have altered in part to bentonite clays.

Volcanic ash is used as an abrasive, mainly in polishing powders, scouring soaps, and cleansing powders; it also is used in pozzolan cement and in insulating compounds.

Miscellaneous Minerals

Several other industrial minerals are present in small or low-grade deposits. Barite nodules, veins, and concretions are sparingly present in some shales and sandstones south of the Wichita Mountains and in central and south-central Oklahoma (Ham and Merritt, 1944). At a few localities surface concentrations of high-grade nodules may have possibilities for limited production.

Celestite and minor amounts of strontianite are associated with dolomite and gypsum in eastern Washita and Custer counties, but these deposits are small and without commercial merit.

Diatomite deposits, widely scattered in western Oklahoma, are small and low grade.

Phosphate occurs as nodules, plates, and lenses in several limestones and black shales in eastern Oklahoma and the Arbuckle Mountains (Oakes, 1938). The P_2O_5 content of the nodules and plates is generally 15–30 percent, whereas that of selected whole rocks is commonly 1–10 percent.

Quartz crystal occurs as large vein deposits in the Ouachita Mountains, especially in central McCurtain County (Honess, 1923).

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Utah Industrial Rocks and Minerals – Geology, Mining, and Recent Developments

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ABSTRACT

Due to Utah's long, diverse geologic history, the state contains and has produced a wide range of industrial rocks and minerals. In 2006, the produced value of all industrial rock and mineral commodities was a record $811 million (17 percent of the total non-fuel mineral production of Utah and more than $300 per Utah resident). Major commodities produced in 2006 include: salts (halite, potash, and magnesium salts), Portland cement, sand and gravel, carbonates (lime, limestone, and dolomite), phosphate, crushed stone, clays, lightweight aggregate (expanded shale and perlite), gypsum, silica, sulfur and sulfuric acid, and building stone. Commodities produced in smaller amounts include: diatomite, pumice, gemstones, ornamental stone, fluorspar, and mineral and fossil specimens.

Recent industrial mineral trends in Utah included strong performance of construction-related industries (sand and gravel, crushed stone, Portland cement, and lime), opening of new mineral operations, and changes in ownership of Utah companies. New operations included shipment of kaolin from Sandy Wash property (Blawn Mountain area), reopening of the Dragon halloysite mine, potential development of new expanded shale capacity at the Utelite operation, the reopening of the Georgia Pacific wallboard plant in central Utah, and the announcement by Allegheny Technologies of a new titanium sponge plant in Utah. Notable changes in ownership include the purchase of two Utah potash operations by Intrepid Mining LLC.

INTRODUCTION

Purpose and Scope

This report provides a brief overview of the geology and mining of industrial rocks and minerals in Utah, reports on recent developments of those resources, and lists sources of additional information (fig. 1). Due to the breadth of the topic and the lack of information on some segments of the topic, it is impossible to provide a balanced discussion of all commodities and all mining operations. It is particularly difficult to provide an up-to-date summary of all company developments; many smaller operators produce intermittently and mining properties change hands frequently, so detailed discussion is limited to mining operations that were judged to be most significant. For example the building stone quarries and sand and gravel pits are not discussed in detail.

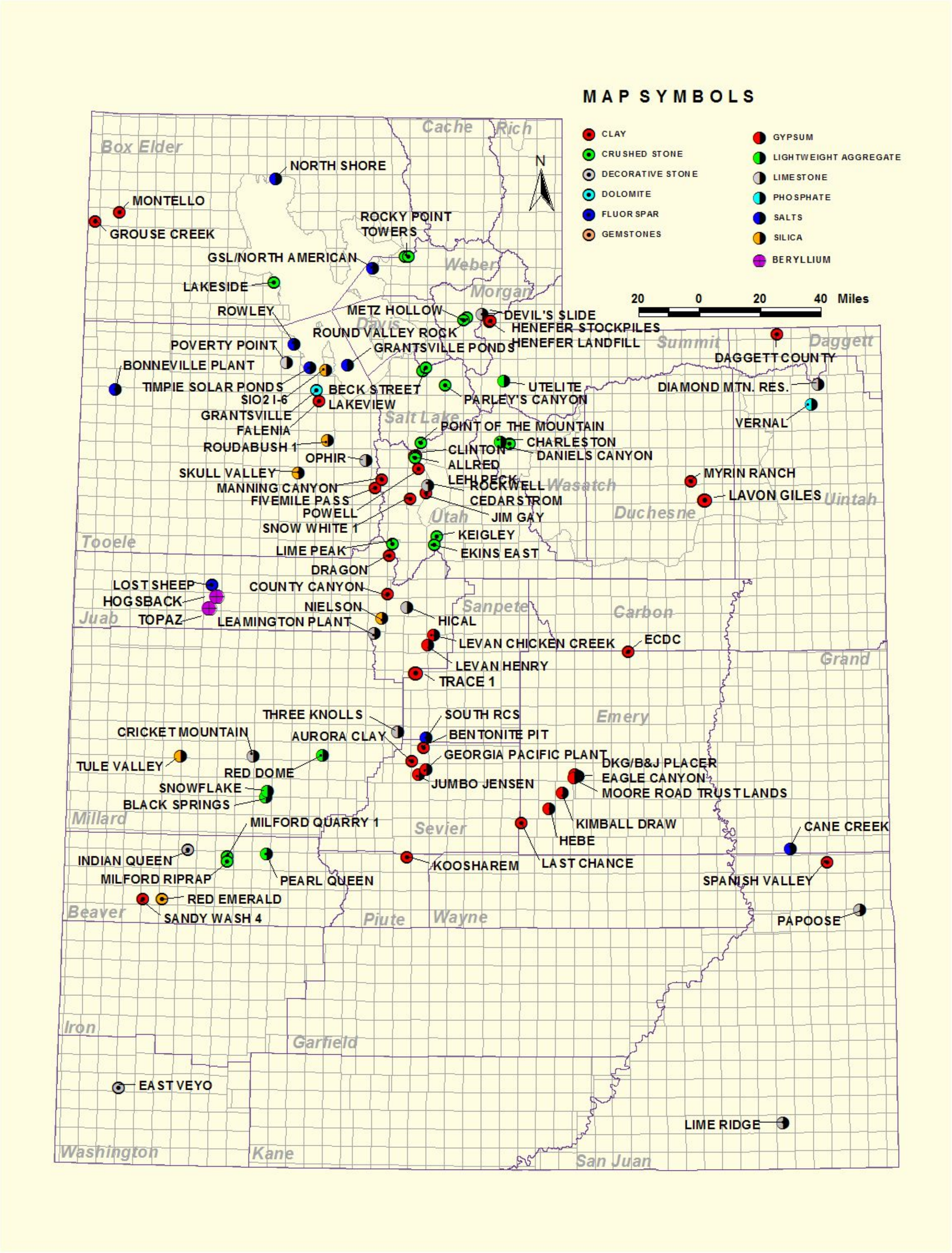

Figure 1. Major Utah industrial mineral pits, quarries, and selected developments.

Data Organization

The commodities discussed in the report are arranged in alphabetical order. Pit locations are shown on Figure 1. Annual mine production data included in the following text are from unpublished data from the Utah Division of Oil, Gas and Mining (UDOGM) if no other source is cited. This production data is volunteered by the mine operators and entered in a working spreadsheet and is not checked for accuracy of original information or accuracy of data entry. All production is reported in short tons unless otherwise stated. This report supercedes earlier published Utah Geological Survey reports on Utah industrial minerals (Tripp, 2001; Tripp, 2007).

Importance of Industrial Minerals in Utah

Mineral production in Utah, including industrial rocks and minerals, reached an all-time high in 2006, proving that the extractive industries are still an important segment of the state's economy. Minerals-industry products (including coal) were valued at $4.68 billion in 2006 (table 1); $811 million of this amount (more than $300 per Utah resident) came from industrial rock and mineral production.

Table 1. Value in 2006 of Utah industrial rock and mineral production relative to other energy and mineral commodities (million $) (Bon and Krahulec, in prep.; Utah Geological Survey, 2007).

Natural Gas	1846 est
Base Metals	2880
Oil	1076 est
Industrial Rocks and Minerals	811
Coal	588
Precious Metals	400

The value of industrial rock and mineral production has risen steadily over the past four years, to an all-time high in 2006 (table 2).

Table 2. Value of industrial rock and mineral production from 1997 to 2006 (million $) (Bon and Krahulec, in prep.).

1997	533	2002	565
1998	534	2003	555
1999	583	2004	643
2000	500	2005	759
2001	538	2006	811

Due to Utah's long, diverse geologic history, the state contains and has produced a wide range of industrial rocks and minerals (table 3). Major commodities produced in 2006 include: salts (halite, potash, and magnesium salts), Portland cement, sand and gravel, carbonates (lime, limestone, and dolomite), phosphate, crushed stone, clays, lightweight aggregate (expanded shale and perlite), gypsum, silica, sulfur and sulfuric acid, and building stone. Commodities produced in smaller amounts include: diatomite, pumice, gemstones, ornamental stone, fluorspar, and mineral and fossil specimens.

Table 3. Industrial rocks and minerals produced in Utah. Commodities in black type were produced in 2006. Commodities in grey normal type have been produced in the past. Commodities in grey italic type are present in the state but are not known to have been produced in commercial quantities.

Main Category	Subcategory
Abrasives	***garnet***
Alunite	
Barite	
Basic refractories	**magnesite**
Beryllium	**bertrandite**
	beryl
Bitumens (solid)	**gilsonite**
	wurtzilite
	ozokerite
	tabbyite
Boron	
Brucite	
Bromine	
Building stone	
Celestite	
Clay	**bentonite**
	common clay
	high-alumina clay
Clinker	
Crushed stone	
Decorative stone	
Diatomite	
Lightweight aggregate	**volcanic cinders**
	expanded shale
	perlite
	pumice
Feldspar	
Fluorspar	
Fossil Specimens	
Gemstones	
Graphite	
Gypsum (*and anhydrite*)	
Humate	
Lime	**high-calcium**
	dolomitic
Mica	
Mineral Specimens	

Pigments	**iron oxide**
Phosphate	**phosphorite**
	guano
Portland cement	
Rare earths	
Salts	**halite**
	potash
	magnesium salts
	sodium sulfate
	lithium
	sodium carbonate
Sand and gravel	
Silica	
Siliceous refractories	***andalucite***
	kyanite
Sulfur	**sulfuric acid**
	by-product elemental sulfur
	natural elemental sulfur
	pyrites
Titanium	
Tremolite	
Vermiculite	
Wollastonite	
Zeolites	
Zirconium	

ALUNITE

Utah contains numerous vein and replacement alunite ($K_2Al_6(OH)_{12}(SO_4)_4$) deposits (fig. 2). Alunite deposits represent an unconventional potash and aluminum resource. These deposits are among the largest of their type in the U.S.; the largest, the NG alunite deposit of Beaver County, contains about 634 million tons of material assaying more than 28 percent alunite (Hall, 1978). Callaghan (1938, 1973), Parker (1964), and many others have described Utah alunite resources.

Small amounts of alunite have been mined during times of unusual mineral economics; a small amount of alunite was mined during World War I for potash and a small amount was mined during World War II for aluminum. An attempt to begin large-scale processing during the 1970s by the Alumet Partnership was unsuccessful; no serious attempt has been made since that time.

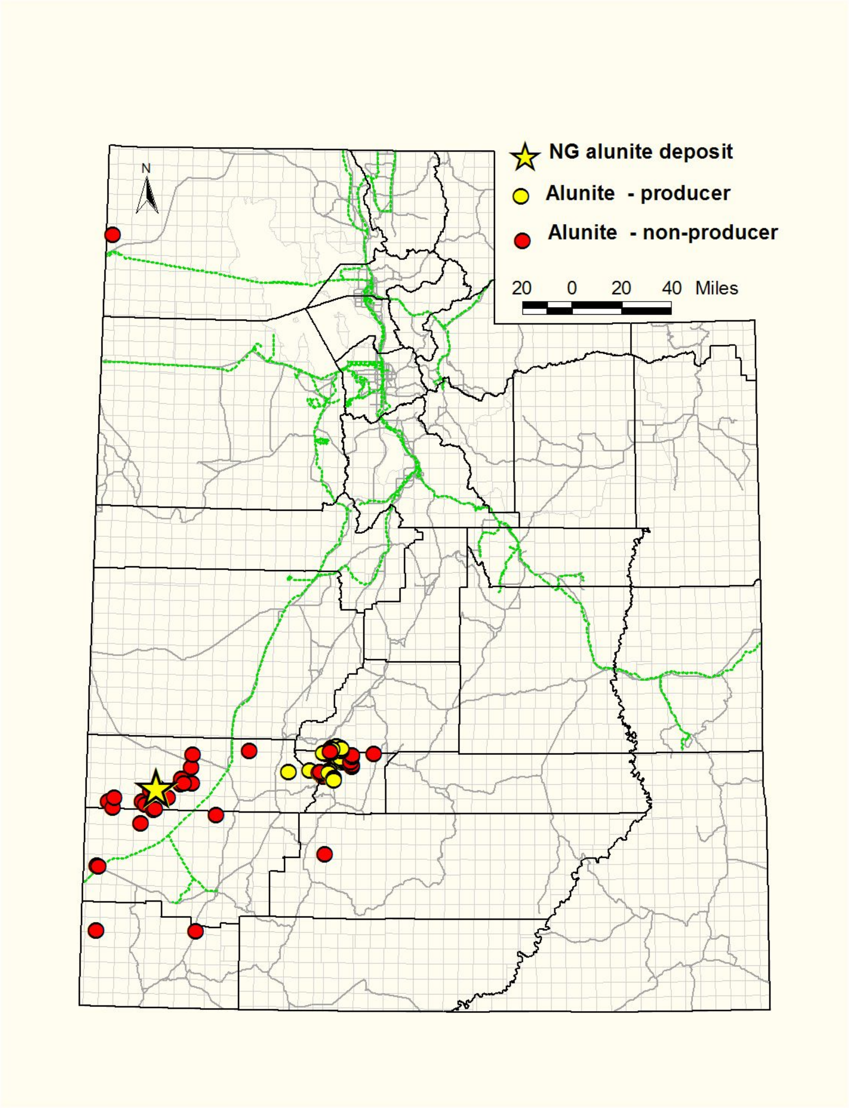

Figure 2. Alunite deposits of Utah; data from Parker (1964) and Thompson (1991).

BERYLLIUM

Brush Resources operates beryllium mines and a processing plant in west-central Utah. Brush mines bertrandite ($Be_4Si_2O_7(OH)_2$) ore near Topaz Mountain at the Topaz and Hogsback mines. The Topaz mine produced 58,661 tons of ore in 2006 and the Hogsback was idle in 2005 and 2006. The bertrandite occurs as a hydrothermal alteration product in rhyolite tuff of the Miocene Spor Mountain Formation beneath flows and domes of topaz rhyolite (fig. 3) (Lindsey, 2001). In their 1998 annual report, Brush reported 7747 million tons of reserves averaging 0.719 percent BeO. The mined ore is hauled to their processing plant near Delta, Utah, where it is converted to beryllium hydroxide. This plant also has a circuit to process imported beryl ore. The resulting beryllium hydroxide is shipped to the Brush Wellman, Inc. plant at Elmore, Ohio for conversion to metallic beryllium, beryllium oxide, and beryllium-containing metal alloys.

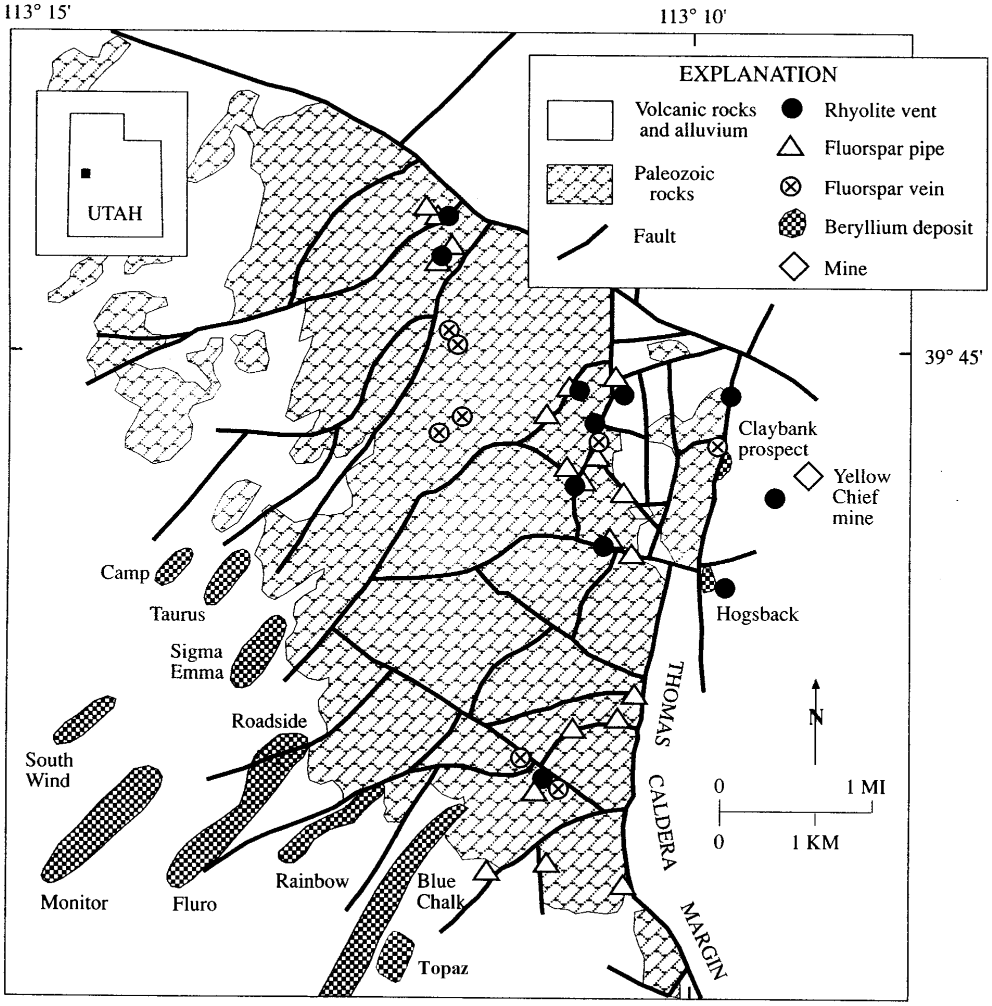

Figure 3. Geologic setting and development of Spor Mountain beryllium deposits, Juab County, Utah (modified from Lindsey, 2001).

BUILDING STONE

Utah building stone companies mine quartzite, sandstone, and limestone (Tripp, 1993). Several companies produce quartzite flagstone and ashlar in northwestern Box Elder County from the Proterozoic Elba Quartzite and Quartzite of Yost, and the Cambrian Clarks Basin Quartzite (Tripp, 1994). Quartzite from Box Elder County has been produced since the 1950s, but the market has been very strong in the past few years because of the robust national and regional housing markets. Tan and red, flaggy to thick-bedded sandstone is quarried from the Jurassic Nugget Sandstone in western Summit County, mostly for the strong local market. Red and tan sandstone blocks are extracted from the Triassic Moenkopi Formation in western Wayne County. Gray sandstone is extracted from southern Duchesne County. A small amount of white, oolitic Tertiary Green River Formation limestone is quarried in south central Sanpete County.

CLAYS

Utah has an assortment of sedimentary and hydrothermal clays including common clay, bentonite, kaolinite, and halloysite that have been produced from a variety of mines (figs. 1 and 4). One of the largest clay producers in Utah is Interstate Brick Company which blends common clays from several quarries to produce many varieties of brick. Interstate's ten permitted pits (with 2006 production in tons in parentheses) are the: Montello (20,000), Fivemile Pass (30,000), Powell (30,000), Jim Gay (0), Allred (0), Snow White 1 (20,000), Henefer Stockpile (0), Henefer Landfill (25,000), Falenia (0), and Manning Canyon pits (0). Interpace Industries, Inc. mined 45,000 tons of clay in 2006 from the Clinton pit in western Utah County for its Weber County brick plant. Interpace has also historically mined clay near Henefer but there has been no production at that location since 2003. The Ash Grove Cement Company mined 38,736 tons of common clay from their County Canyon pit in eastern Juab County in 2004 (but no production was reported in 2005 or 2006) for use at their nearby Leamington plant. W.W. Clyde permitted two clay operations in Duchesne County: the Myrin Ranch and Giles pits. Their Myrin Ranch pit produced about 140,000 cubic yards of clay in 2005 and a much smaller amount in 2006 for use in reconstructing the Big Sand Wash Reservoir. W.W. Clyde did not mine clay at the Giles pit because they were able to extract enough clay from the Myrin Ranch pit to complete the job. W.W. Clyde also mined sand and gravel nearby for the same project (Clark Prothero, W.W. Clyde, personal communication, October 27, 2006)

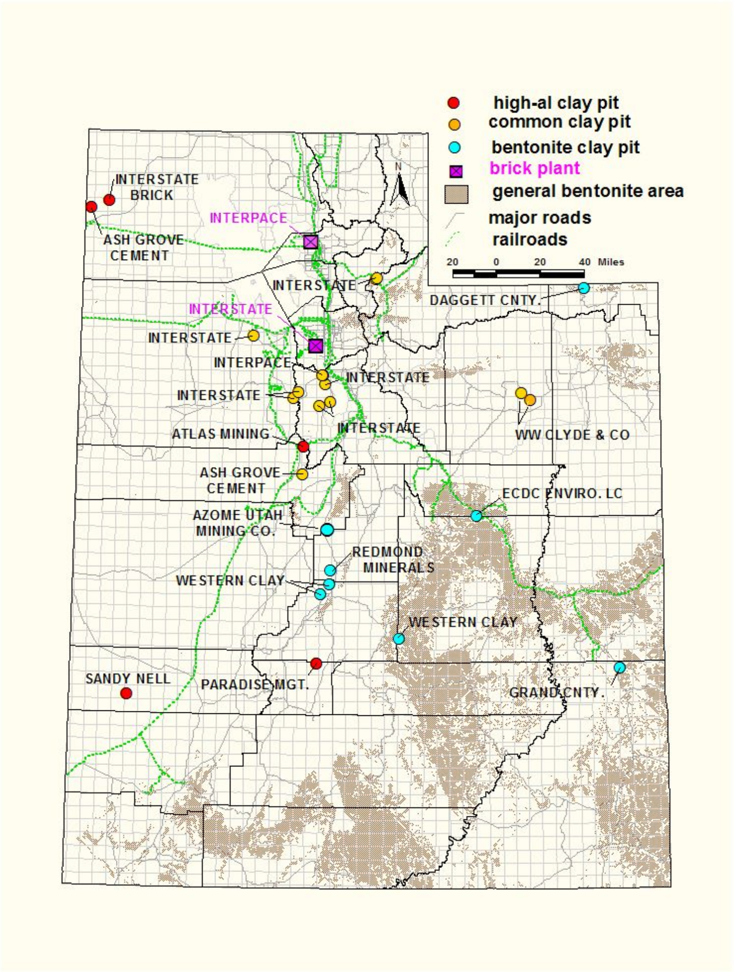

Figure 4. Location of significant clay pits in Utah.

Redmond Minerals, Inc. produces bentonite from their South RCS mine in southern Sanpete County for use in construction and well-drilling fluids. Redmond produced 389,985 tons of rock salt and bentonite from this property in 2005. In 2006, Western Clay Company produced 65,000 tons of bentonite from the Bentonite pit in northern Sevier County and 600 tons of bentonite from their Last Chance pit in southwestern Emery County. Western last produced Fuller's earth (bentonite) from their Aurora Clay mine in northern Sevier County in 2004. ECDC Environmental L.C. has produced and stockpiled bentonite from northern Emery County but has not produced since 2000. ECDC mines bentonite clay for construction of waste-containment cells at their massive landfill site in eastern Carbon County. Grand County mines bentonite from their Spanish Valley Clay pit in northern San Juan County to line water canals. They mined 2242 tons of clay in 2006. Daggett County periodically mines bentonite clay in northern Daggett County for construction use, but their last production was in 2003. The Azome Utah Mining Company, Inc. mined 4731 tons of montmorillonite from the Tertiary Goldens Ranch Formation in Sanpete County in 2006. This material is custom processed and bagged by Western Clay and marketed by Peak Minerals - Azomite, Inc. under the registered trademark Azomite ® for animal and plant nutritional supplement (Peak Minerals – Azomite, Inc., 2007).

High-alumina clays, like kaolinite and halloysite, were explored for and mined in Utah in 2006. The Ash Grove Cement plant in Inkom, Idaho has mined some kaolinite from their Grouse Creek clay pit in western Box Elder County, Utah as a source of alumina for manufacture of low-alkali-reactivity Portland cement, but the pit has been inactive since 1998. Holcim, Inc. purchased kaolin from Paradise Management Corp.'s Koosharem property in northern Piute County as a source of alumina for their cement plant in central Morgan County. This deposit consists of altered tuffaceous rock within the ring fracture system of a caldera. The Koosharem pit produced 21,339 tons of clay in 2006. Atlas Mining continued to evaluate their Dragon halloysite mine in the Tintic mining district, research applications for the clay, and develop markets but did not produce commercial quantities of clay in 2005 or 2006. Sandy Nell explored for kaolinite in west and central Utah and produced 80,000 tons from the Sandy Wash 4 (Blawn Mountain) property in Beaver County in 2006.

CRUSHED STONE

Nearly unlimited sources of high-quality rock suitable for crushed stone occur throughout Utah. The importance of this resource will increase as sand and gravel deposits in urban areas are depleted or made inaccessible by residential development, and as material specifications become more stringent. Production of crushed stone for aggregate has created a regulatory debate in Utah. Many large sand and gravel operations along the Wasatch Front (from Utah County on the south to Weber County on the north) have seamlessly progressed from mining sand and gravel to mining both sand and gravel and brecciated bedrock from the same pits often with few changes in their mining techniques. The State of Utah specifically exempts sand and gravel from regulation and bonding, but as soon as operators start removing bedrock they are required to file reclamation permit applications and post bonds with UDOGM. Several sand and gravel pits continued mining into the bedrock beneath the sand and gravel and have become subject to reclamation permitting by UDOGM. They are listed in Table 4 below and plotted on Figure 1.

Table 4. Sand and gravel pits with co-product crushed stone.

Company	Pit Name	Year (tons produced)
Staker and Parsons Companies	Beck Street	2006 (3,545,556)
Lakeview Rock Products	Lakeview	2006 (1,473,000)
Geneva Rock Products, Inc.	Point of the Mountain (So. Hansen)	2006 (6,385,826)
West Valley Sand and Gravel, Inc.	Daniels Canyon	2005 (369,496)
Orton Ranch and Development	Rocky Point	2004 (22,017)
Towers Sand and Gravel	Towers	n.a.

In 1997, Twin Mountain Rock Co. opened a railroad ballast quarry in central Beaver County in a Tertiary quartz monzonite porphyry. Twin Mountain produced 1,000,000 tons of ballast in 2005 from their Milford Quarry 1. Their adjacent Milford – Riprap pit has been inactive since 2001. Reserves were estimated to be roughly 25 million tons of rock in 1997 (UDOGM unpublished files, 2000). Twin Mountain was a subsidiary of Peter Kiewit and Sons until 2002 when Kiewit's quarry operations were purchased by Rinker Materials.

In 2006, Staker and Parsons Companies mined 807,871 tons of limestone from the Lehi Peck quarry in northern Utah County for aggregate. The Lehi Peck pit, in the Mississippian Great Blue Limestone, began production in 1998. They also mined 616,411 tons of Cambrian limestone and dolomite in 2006 for crushed stone from the Keigley quarry in Utah County. Staker and Parsons has not mined their Ekins East pit (in the Mississippian Deseret Limestone) since 2003.

Shaw Environmental, Inc. mined 263,844 cubic yards of limestone from their Lime Peak quarry, in western Utah County, in 2006 for use as riprap in the Superfund cleanup a few miles to the west in the nearby Tintic metals mining district. The quarry is in the Mississippian Gardison and Fitchville Formations. The quarry was operated decades ago by Chief Consolidated mining company as the source of high calcium limestone for an adjacent lime plant.

Round Valley Rock mined 250,000 tons of limestone in 2006 for aggregate from their pit in Morgan County.

Cable Mountain L.L.C. mined 522,428 tons of limestone in 2006 from the Mississippian Deseret Limestone at their Rockwell mine (formerly the Larson Limestone property) in western Utah County. In the 1990s, some higher calcium carbonate material from this pit was selectively mined for use in flue-gas desulfurization and for use as flux at Kennecott, so this quarry has potential to produce high-calcium limestone.

Wilkinson Construction has not mined their Metz Hollow pit in central Morgan County since 2003. This pit has typically produced crushed limestone for aggregate.

Harper Contracting, Inc. continued operating the Parley's Canyon quarry in eastern Salt Lake County. In 2006 they produced 677,706 tons of crushed Jurassic Twin Creek Limestone for aggregate.

Red Dome, Inc. continued production of volcanic cinders in southeastern Millard County. The company last reported production of 16,000 tons in 2003. Much of this material was sold for landscape rock mulch. Sunroc also mines cinders from their East Veyo pit in Washington County; they reported production of 15,000 tons in 2005.

Union Pacific occasionally quarries and crushes stone from their Lakeside quarry in southern Box Elder County. The quarry is located in the Mississippian Great Blue Limestone on the west end of the Great Salt Lake railroad causeway. Much of the material mined has been used for construction and maintenance of the railroad causeway across Great Salt Lake.

Some recycled construction materials compete with sand and gravel and crushed stone production. In 2004, Utah companies processed 205,000 metric tons of recycled asphalt paving worth $697,000 and 16,000 metric tons of concrete worth $47,000 (Bolen, 2005). In 2005, the amount and value of recycled asphalt was not reported, but Utah ranked third behind California and Minnesota. Granite Construction, which produces sand and gravel in Utah, was the leading asphalt pavement recycler in the U.S. in 2005. In 2005, Utah industry only recycled 1000 metric tons of concrete worth $3000 (Bolen, 2007).

DIATOMITE

Holcim (US), Inc's, Skull Valley pit produced 11,860 tons of diatomite in 2006 from Pleistocene Lake Bonneville sediments in southeastern Tooele County. Some information on the diatomite in Lake Bonneville sediments is contained in Setty (1963) and Doelling, (1979). The deposit is reported to be about 30 feet thick. The material was shipped to Holcim's Devils Slide cement plant for use as a pozzolanic additive. Holcim is in the process of converting their UDOGM permits from Small Mine to Large Mine status (Thomas Newman, Holcim (US), Inc., personal communication, October 2006.)

EXPANDED SHALE

The Utelite Corporation mines the organic-rich, argillaceous Cretaceous Frontier Formation, from the Utelite pit in western Summit County. The mined material is expanded in four rotary kilns (fig. 5) into a lightweight product which is used as aggregate in concrete roofing tiles, concrete blocks, and structural concrete, and for miscellaneous uses such as horticulture, highway construction, and loose fill. Utelite mined 249,371 tons of shale in 2006. Utelite is considering additional development at their Grass Creek property that is also located in Summit County.

Figure 5. Utelite Corp.'s expanded shale plant in western Summit County; Rockport Reservoir is in the background (view is to the northeast).

FLUORSPAR

Utah contains several mining districts that produced fluorspar starting as early as 1918 (Bullock, 1976). There has been only small sporadic production for the last few decades. Michael Provstgaard produced small amounts of fluorspar from pipe deposits at the Lost Sheep mine in the Spor Mountain mining district; his production in 2006 was 619 tons.

GEMSTONES, ORNAMENTAL STONE, AND MINERAL AND FOSSIL SPECIMENS

Utah has long produced semi-precious gemstones, decorative stone, and mineral and fossil specimens on a small scale. Utah gemstone companies sporadically produce blue celestite, topaz, amethyst, and red beryl. Utah decorative stone production includes small amounts of banded rhyolite, marble, onyx, alabaster, scoria, obsidian, black- and white-banded dolomite, travertine and tufa, sandstone and tuffaceous picture stone, aragonite, and opal. Utah companies also mine the following fossil and mineral specimens: azurite and malachite, geodes, septarian nodules, garnet, bixbyite, variscite, hematite, calcite, selenite, and trilobites.

Utah is well known for its topaz-rhyolite-associated red beryl occurrences. The origin of these deposits was researched by Keith and others (1994) and Christiansen and others (1996). Five companies have mining permits for red beryl, but only the Red Emerald mine in Beaver County has produced recently (Tom Munson, 2006, UDOGM, verbal communication). Another notable operation is the Indian Queen marble quarry in the Frisco mining district. Indian Queen

LLC mines and crushes white and pink contact metamorphic marble and sells most of it for landscape granules. Their operation was active in 2006, but their last documented production was 7634 tons in 2002.

GILSONITE

Gilsonite is a black, shiny, lightweight, naturally occurring hydrocarbon (asphaltite) that occurs in vertical veins in the Uinta Basin of eastern Utah (fig. 6) (Tripp and White, 2006). It has a long mining history and is still mined by three companies, American Gilsonite Company, Ziegler Chemical and Mineral Corporation, and Lexco, Inc. Combined production from the three companies has been substantially less than 100,000 tons per year, but Gilsonite is a high unit value commodity especially in its processed forms.

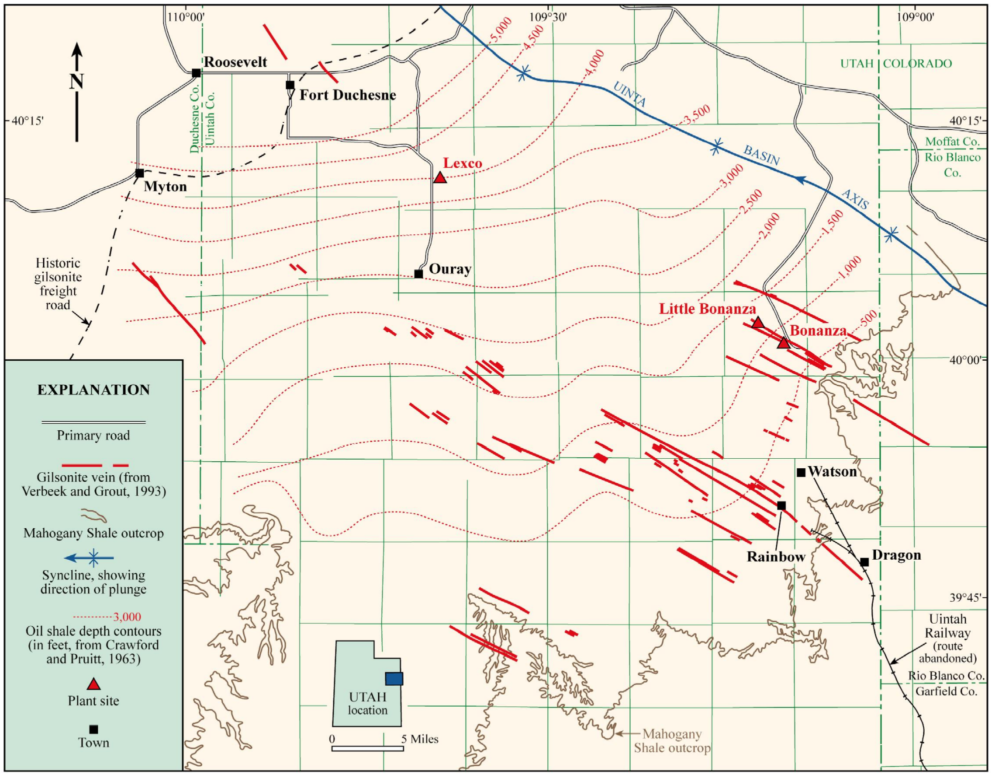

Figure 6. Location and geologic setting of gilsonite veins, Uinta Basin, Utah (from Tripp, 2004).

GYPSUM

Utah has one of the largest gypsum resources in the U.S.. Withington (1964) estimated reserves of 2 billion tons averaging more than 85 percent gypsum in beds a minimum of 4 feet thick within 30 feet of the ground surface. Whereas numerous geological formations contain gypsum, the Pennsylvanian Paradox Formation of the Hermosa Group, the Jurassic Arapien Shale, the Jurassic Summerville Formation, and the Jurassic Carmel Formation contain most of the resource. Most of the production is from central Utah (fig. 7) and it is used in the manufacture of wallboard, but some is used for Portland cement retarder, agricultural gypsum, wallboard joint compound, and plaster.

U.S. Gypsum Company has long mined Jurassic Arapien Shale gypsum at the Jumbo Jensen quarry near their Sigurd wallboard plant in east-central Sevier County for the manufacture of wallboard, plaster, and wallboard joint compound. The Jumbo Jensen quarry produced 151,655 tons of gypsum in 2006. U.S. Gypsum did not mine from their San Rafael/Kimball Draw or Moore Road Trust lands gypsum mines in southwest Emery County in 2006.

Georgia Pacific Corporation, a long-time Utah gypsum wallboard producer, built a new wallboard plant near Las Vegas and closed their older Sigurd plant in Sevier County but reopened the Sigurd plant in 2006. Georgia Pacific has three gypsum mines in Utah: the quarry at their wallboard plant in the Jurassic Arapien Shale, and the Eagle Canyon and Hebe mines in Emery County in the Jurassic Carmel Formation. Georgia Pacific mined 128,868 tons from the Eagle Canyon mine in 2006, but did not mine the Hebe in 2006. Georgia Pacific also purchased gypsum from the DKG pit of Diamond K. Gypsum.

Sunroc Corporation (a subsidiary of Clyde Companies, Inc.) mined gypsum from two mines in the Jurassic Arapien Shale near Levan in Juab County in 2006. The Levan Chicken Creek mine produced 102,136 tons and the Levan Henry mine produced 9607 tons.

Diamond K. Gypsum Industries, Inc. mines Carmel Formation gypsum from their DKG / B&J placer claims in southwestern Emery County. In 2006, Diamond K. Gypsum produced 59,755 tons of gypsum; some of the material was sold to Georgia Pacific. The gypsum has also been shipped for use as an agricultural soil conditioner (Welsh, 2001).

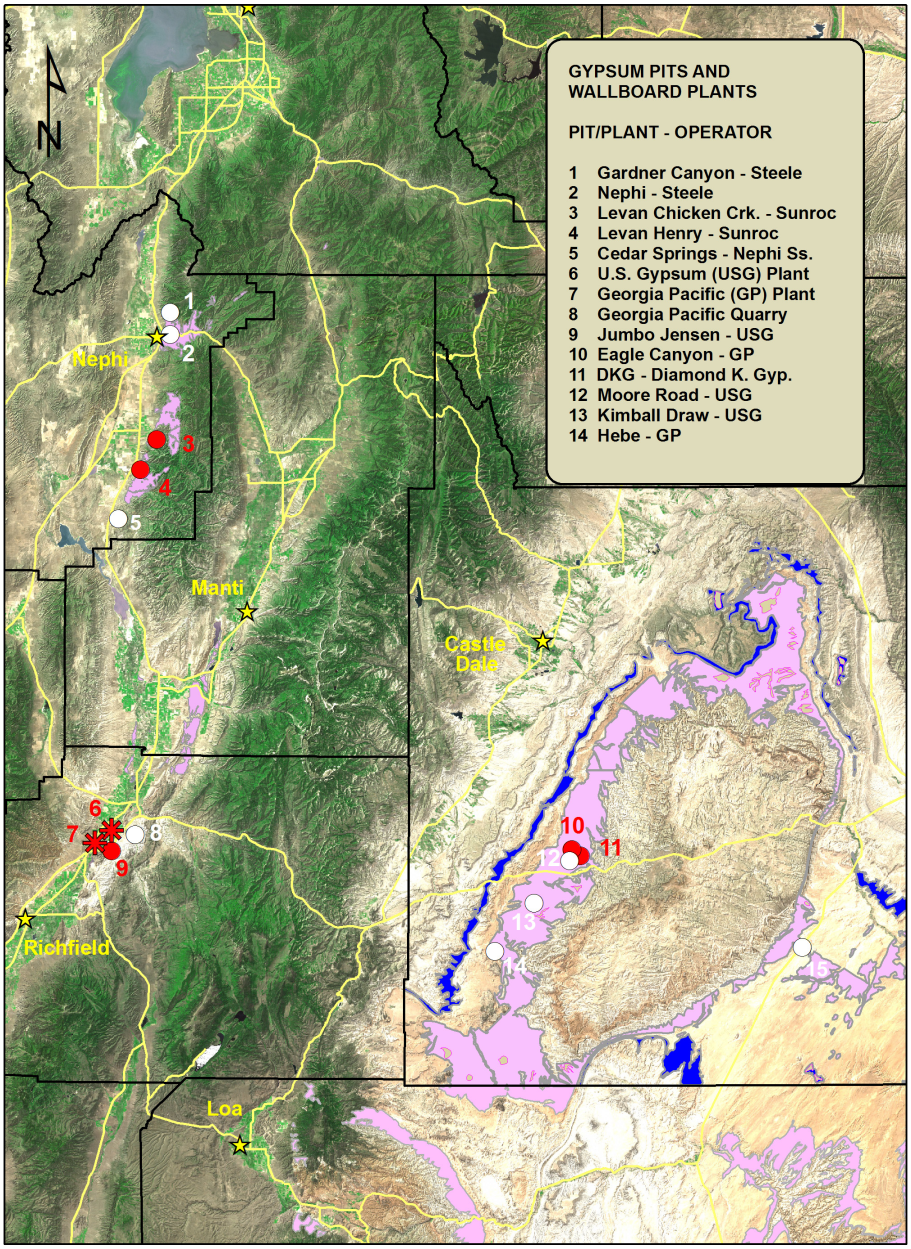

Figure 7. Central Utah gypsum industry. Red stars are active wallboard plants, red dots are active gypsum pits, and white dots are inactive gypsum pits. Pink areas forming a circle around the San Rafael Swell are outcrops of the gypsiferous Jurassic Carmel Formation. Blue areas forming a circle around the San Rafael Swell are outcrops of the gypsiferous Jurassic Summerville Formation. Pink areas in the area around Nephi and south toward Richfield are outcrops of the gypsiferous Jurassic Arapien Shale. Yellow lines are highways and yellow stars are county seats.

HALITE

Significant halite resources occur at seven locations in Utah (fig. 8): (1) in surface brines of Great Salt Lake, (2) in salt beds and subsurface brines of the Pennsylvanian Paradox Formation of the Hermosa Group in the Paradox basin, (3) in subsurface brines in Holocene and Quaternary sediments of the Great Salt Lake Desert, (4) in salt beds of the Jurassic Arapien Shale of Sevier and Sanpete counties, (5) in subsurface brines in Holocene sediments of the Sevier Lake playa, (6) in a Tertiary salt dome of northern Millard County, and (7) in salt beds of the Jurassic Preuss Sandstone of northeastern Utah.

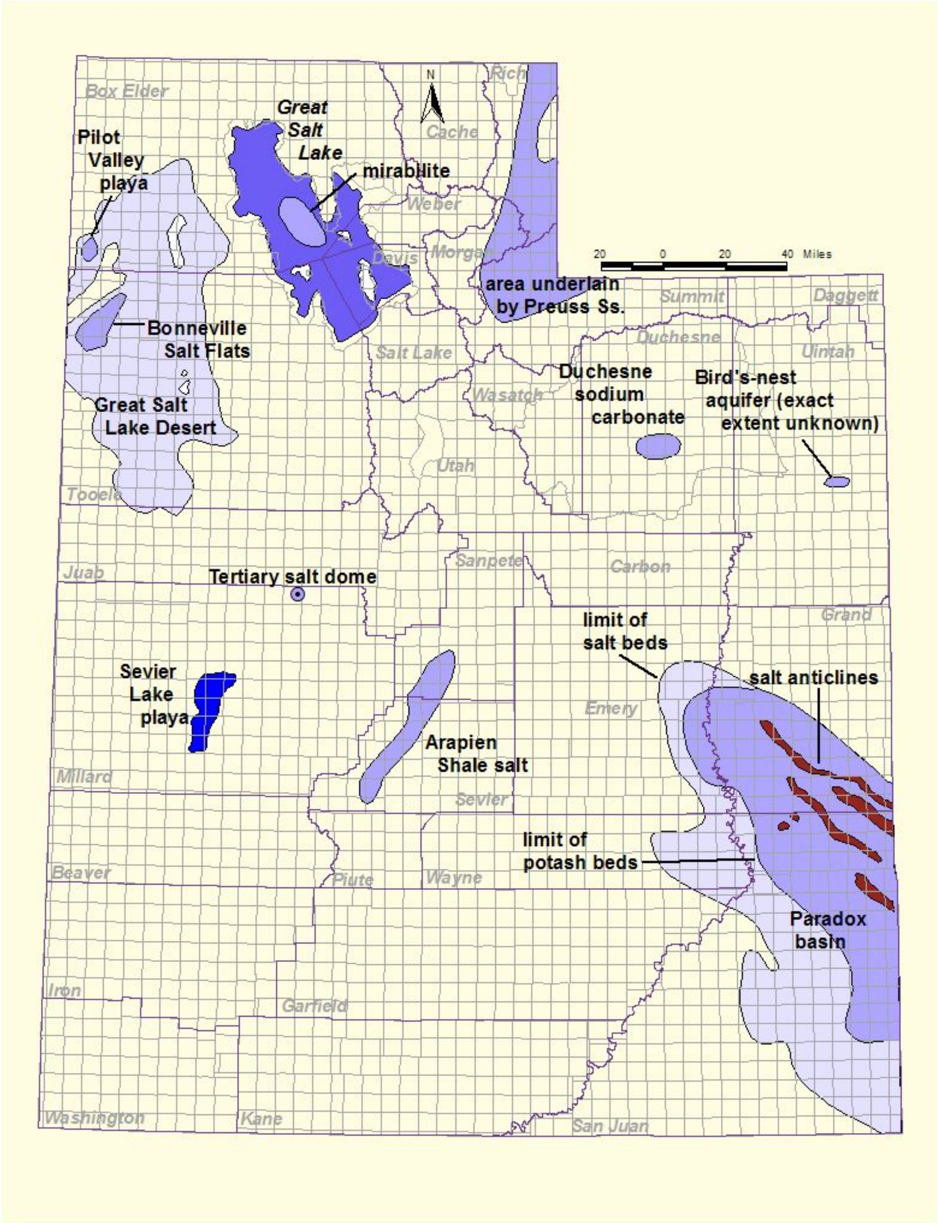

Figure 8. Salt resources of Utah (modified from Elston and Shoemaker, 1963; Hite, 1964; Parker, 1964; and Dyni, 1996).

Great Salt Lake

Great Salt Lake has long been an important producer of halite by solar evaporation of surface brines in shallow harvest ponds (Gwynn, 2006b). Production from Great Salt Lake accounted for the bulk of the 2.9 million tons of salt produced in Utah in 2005 (Bon and Krahulec, 2006) and the 2.77 million tons of salt produced in 2006 (Bon and Krahulec, in prep). The lake consists of two distinct brine bodies, the north and the south parts of the lake are separated by the Union Pacific Railroad causeway. Depending on amount of precipitation, the two parts often differ greatly in salinity with the north arm generally being saltier. The lake brine contains commercial concentrations of sodium, potassium, and magnesium salts, but is not anomalously rich in other salable commodities such as lithium, bromine, and boron (Sturm, 1980). Three companies currently produce halite from Great Salt Lake: North American Salt Co., a division of Compass Minerals, in western Weber County (Butts, 2002), Morton International, Inc., a subsidiary of Rohm and Haas, in northeast Tooele County (Tuttle and Huizingh, 2002) (fig. 9), and Cargill Salt, Inc. (also in northeast Tooele County). North American Salt has an annual plant capacity of about 1.5 million tons of halite. Cargill Salt produced 743,762 tons of halite from their Timpie solar ponds in 2006. Morton International, Inc. produced 561,542 tons of salt from their Grantsville solar pond facility in 2006 (fig. 9).

Figure 9. Solar salt harvesting equipment at Morton International, Inc.'s solar evaporation ponds on the south end of Great Salt Lake, Utah.

There have been ownership changes in the Great Salt Lake salt industry over the past several years. In November 2001, IMC Global Inc. sold its two divisions on the Great Salt Lake, IMC Kalium Ogden Corp. and IMC Salt Co., to Apollo Management LP which created a new entity named Compass Minerals Group that is headquartered in Overland Park, Kansas (Butts, 2002). Two divisions of Compass Minerals, Great Salt Lake Minerals Corp (GSL) and North American Salt Company, share facilities on the Great Salt Lake. GSL produces and markets potash (potassium sulfate) and North American produces and sells halite and magnesium chloride.

Other Halite Deposits

The other halite deposits in Utah contain large resources, but have produced relatively small amounts of halite compared to Great Salt Lake. In the Paradox basin, in southern Grand County, Intrepid Potash – Moab LLC (previously Moab Salt, Inc.) recovers halite as a by-product of potash mining. Intrepid Potash - Moab solution mines evaporite salt beds of the Pennsylvanian Paradox Formation (salt cycle five) at the Cane Creek mine and processes the resulting brine by solar evaporation.

Intrepid Potash – Wendover LLC's Bonneville plant (previously Reilly Wendover) in the Great Salt Lake Desert in western Tooele County has produced large amounts of halite as a by-product of potash production at their Bonneville plant. Most of the halite remains in the evaporation ponds where it precipitated during a preliminary step in potash recovery; only small quantities of the halite have been shipped to market.

In southern Sanpete County, Redmond Minerals mines rock salt underground at the South RCS mine from a salt antiform in the Jurassic Arapien Shale (fig. 10) (Pratt and others, 1965). The salt antiform is approximately 1,000 feet across, 1,000 feet thick, and could be more than 5 miles long. Additional thick salt layers have been penetrated in nearby drill holes (Willis, 1991). Redmond mines both salt and clay from this property so their production of 389,985 tons in 2005 includes clay and halite. This rock salt is primarily sold for livestock salt and as a health-food table salt (Eborn, 2006).

Figure 10. Portal of the South RCS underground rock salt mine in Sanpete County, Utah.

In 1993, Crystal Peak Minerals attempted to produce halite from subsurface brines of the Sevier Lake playa (fig. 8) in south-central Millard County (Gwynn, 2006a), but the operation was suspended due to lack of a market and funding. In northern Millard County oil and gas drilling at the Argonaut Energy No.1 Federal well revealed the presence of a salt body (fig. 8) in Tertiary rocks 2550 feet below the surface. The salt section in this well is more than 5,000 feet thick and extends roughly five miles east-west (Mitchell, 1979). The north-south extent of the deposit is not known and the deposit has not been developed. In Summit and Rich counties, the Jurassic Preuss Sandstone (fig. 8) contains a large amount of salt in the subsurface. More than 2000 feet of salt occurs in northernmost Summit County although this thickness probably reflects salt flowage and the effects of Sevier-age thrusting (Lamerson, 1982). Preuss salt has not been mined in Utah, but has been produced in small quantities in Idaho (Mansfield, 1927).

HUMATE

Eleven humate mines are permitted by DOGM in Emery and Wayne counties. A few of these mines produced a small amount of humate mostly from the Cretaceous Ferron Sandstone Member of the Mancos Shale in Emery County (Gloyn and others, 2003). Some of the humate is vat leached with water and the resulting liquid sold as a human trace element nutritional supplement.

LIME, LIMESTONE, AND DOLOMITE

Cambrian to Mississippian geologic formations are the source of most of Utah's carbonate production (Tripp, 2005). Calcite veins, tufa mounds, and oolitic sands from Great Salt Lake are other sources of present or past production. Eight operators in Utah produce a wide variety of carbonate products,

Graymont Western U.S., Inc., in central Millard County, mined 2,268,882 tons of limestone and dolomite in 2006 for calcining in four rotary kilns at their Cricket Mountain facility (fig. 11). Cambrian Dome Formation limestone is mined and crushed at their Flatiron pit and then is trucked 6.5 miles east to their plant on the Bloom railroad siding of the Union Pacific Railroad. The company produces dolomitic lime from the B.B. Claims pit. The B.B. Claims pit is in the Cambrian Limestone of the Cricket Mountains (Hintze, 1984).

Figure 11. Graymont Western's Cricket Mountain facility, Millard County, Utah (from Graymont Ltd, 2007).

Chemical Lime of Arizona, Inc. mined 200,000 tons of Ordovician Fish Haven Dolomite at their Grantsville facility (fig. 12) in northeastern Tooele County for production of dolomitic quicklime and hydrated lime (Type S). Coal is their primary fuel augmented by a tire burner connected to their rotary kiln. In 1995, Chemical Lime purchased the old Utah Marblehead Lime plant, at Delle in northern Tooele County, from U.S. Pollution Control, but it is not currently operating. The Delle facility originally processed Ordovician Fish Haven Dolomite into dead-burned dolomite for manufacture of refractories used in the steel industry.

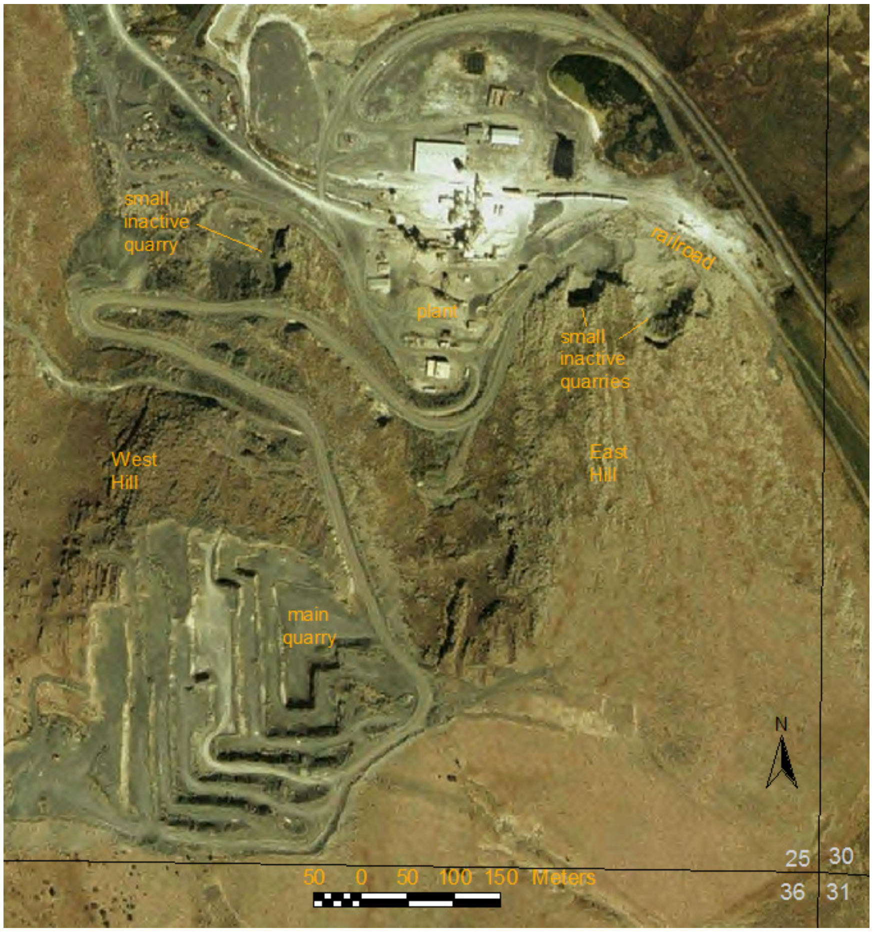

Figure 12. Air photo of Chemical Lime of Arizona's dolomitic lime plant and quarry at the north end of the Stansbury Range in Tooele County, Utah (map base from U.S. National Agricultural Image Program 2006 imagery).

Cotter Corporation mined 113,121 tons of limestone in 2005 from the Pennsylvanian Honaker Trail Formation of the Hermosa Group at its Papoose quarry in northern San Juan County. This product is trucked 65 miles to Nucla, Colorado where it is used for flue-gas desulfurization in a small electric power plant (Reed, 1996).

Western Clay Company mined 30,000 tons of limestone in 2006 from their Three Knolls limestone quarry in the Tertiary Flagstaff Limestone of eastern Millard County probably for coal-mine rock dust and crushed stone.

Cedarstrom Calcite produced 6,798 tons of vein calcite in 2005 from their underground calcite mine in the Mississippian Deseret Limestone and Humbug Formation of western Utah County. A major use of this material is for poultry grit.

Deseret Generation and Transmission Co. opened the Diamond Mountain Resources limestone quarry (fig. 13) in 1999 in Mississippian Madison Limestone to provide limestone for flue-gas desulfurization at their Bonanza power plant in east-central Uintah County. The quarry, located in northern Uintah County, produced 106,145 tons of limestone in 2006. The limestone is mined and crushed by contractors and shipped south to the power plant where it is pulverized prior to use.

Figure 13. Mobil crusher processing Mississippian Madison Limestone at the Diamond Mountain limestone quarry on the south flank of the Uinta Mountains in Uintah County, Utah

Holcim, Inc. mined 18,860 tons of limestone in 2006 from the Mississippian Great Blue Limestone at their Poverty Point quarry in eastern Tooele County for raw material for their Devil's Slide cement plant in Morgan County.

Broken Arrow Resources (of which MacFarland and Hullinger is a subsidiary) mined 10,000 tons of limestone from the Cambrian Bowman Limestone at the Ophir limestone quarry in eastern Tooele County in 2005, but did not produce in 2006.

Robert and Terry Steele produced 15,000 tons of limestone in 2005 from travertine in the Tertiary Sage Valley Limestone Member of the Goldens Ranch Formation at their Hical quarry in eastern Juab County, but did not produce in 2006.

NON-HALITE SALTS

Four localities in Utah contain large quantities of potassium and magnesium salts and sodium sulfate: Great Salt Lake, the Great Salt Lake desert, the Paradox Basin, and Sevier Lake. In addition, the Uinta Basin in Duchesne and Uintah counties contains bedded sodium carbonate and sodium carbonate rich brines (fig. 8).

Great Salt Lake

Three Great Salt Lake operations produce salts other than halite: U.S. Magnesium, Great Salt Lake Minerals, and North Shore Ltd. Partnership. U.S. Magnesium produces magnesium chloride brine through solar evaporation at their Rowley plant for conversion to magnesium metal, liquified chlorine, calcium chloride, ferrous and ferric chlorides, and other byproducts (Tripp, 2002). U.S. Magnesium's plant (the only primary magnesium metal plant in the U.S.) (fig.14) currently produces about 47,000 tons of metallic magnesium per year (Mining Engineering, 2007) and started an expansion a few year ago that would have boosted production to about 57,000 tons; the expansion was shelved because of low magnesium prices. Prices have recently rebounded from \$1.10 – \$1.17 per pound in 2003 (Kramer, 2006) to \$1.55 – \$1.60 in February 2007 (Mining Engineering, 2007). Additional good news for U.S. Magnesium was the announced construction of an Allegheny Technologies titanium sponge plant adjacent to the Rowley magnesium plant (see titanium section of this paper).

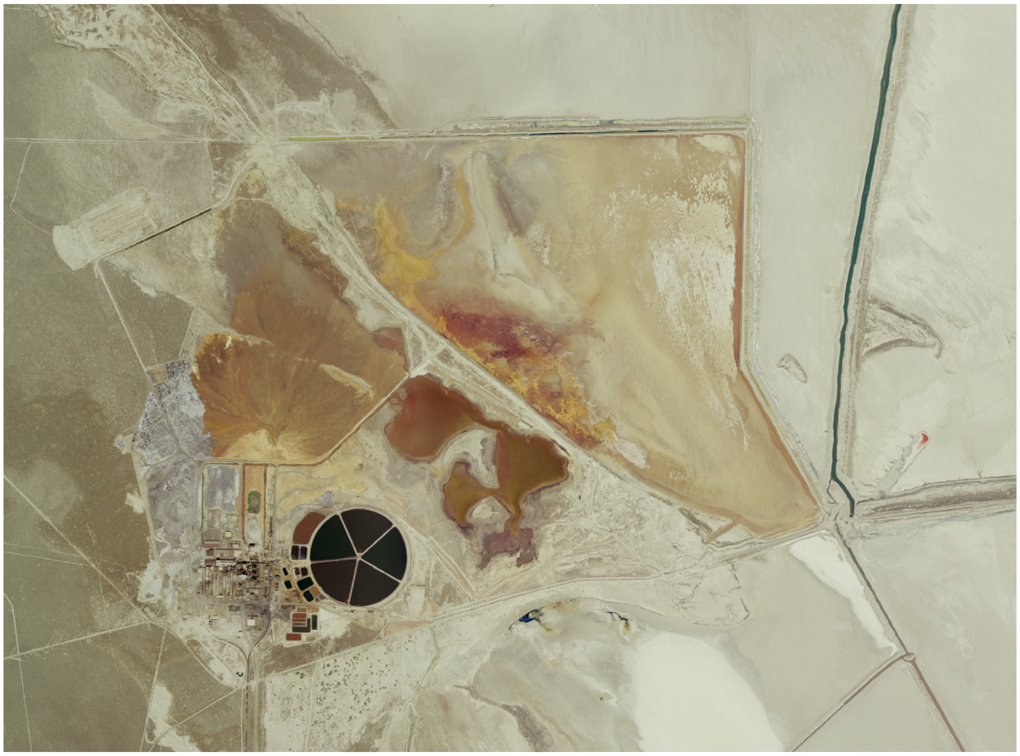

Figure 14. U.S. Magnesium's Rowley magnesium plant on the west side of Great Salt Lake, Tooele County, Utah (map base from U.S. National Agricultural Image Program 2006 imagery). Top of map is north and the large "spoked" circular feature east of the plant is the deep brine storage pond that holds feedstock for the plant.

Great Salt Lake Minerals Corporation (GSL), a division of Compass Minerals of Overland Park, Kansas, produces potassium sulfate (potash) from the brine of the Great Salt Lake and imported Canadian potassium chloride (Butts, 2002) using two 20,000-acre solar evaporation ponds. They are the largest producer of potassium sulfate in North America. Potassium sulfate is primarily used in plant fertilizer and is particularly valuable in NaCl sensitive fields due to its low chloride content. GSL maintains the chloride content of its product at less than 0.8 percent chloride (Great Salt Lake Minerals Corp., 2006).

North American Salt (another division of Compass Minerals that is co-located with GSL) produced magnesium chloride from the lake. Their magnesium production capacity in 1997 was 117,000 tons (Kramer, 1997). Magnesium chloride is used for dust control on dirt roads, as an oil well drilling fluid additive, as a dessicant, as a fire-retardant coating, for animal and plant nutritional supplement, and for a wide variety of other industrial and chemical processes.

Another interesting brine operation on Great Salt Lake is the North Shore Ltd. Partnership (Anderson and Anderson, 2002) in northern Box Elder County, which, in 2005, concentrated 100 acre-feet of lake brine through solar evaporation to produce a trace element nutritional supplement.

The potash resource in the Great Salt Lake brine is estimated to be 100 million tons of K_2O equivalent (Adams and Hite, 1983). An additional saline resource, buried at shallow depth within the Quaternary sediments in the center of Great Salt Lake, consists of a bed of mirabilite (a hydrated sodium sulfate) which reaches a maximum thickness of about 32 feet. Construction crews discovered the mirabilite (fig. 8) while building the original wooden railroad trestle across Great Salt Lake in 1903 (Hite, 1964); this resource has never been developed.

Great Salt Lake Desert

Intrepid Potash – Wendover LLC's Bonneville potash plant produces standard-grade and coarse-grade potassium chloride (potash) and liquid magnesium chloride from brines of three subsurface aquifers at the Bonneville Salt Flats in western Tooele County. In 2006, they produced a total of 394,633 tons of salt products at their Bonneville plant. The shallowest aquifer, generally less than 20 feet deep, provides most of the brine, which is gravity drained through canals toward the plant. The brine is evaporated in a series of solar ponds. Different salts precipitate sequentially based on their solubilities. Sylvinite (a sylvite/halite salt mixture) is harvested from the ponds and trucked to the Bonneville plant. A froth flotation circuit separates the valuable sylvite from the sylvinite. Less concentrated brine from a deep aquifer is produced from wells as deep as 2051 feet. Wells as deep as 200 feet, in an alluvial-fan aquifer to the north of the Bonneville plant, provide brackish water used in the plant for processing sylvite (Bingham, 1980). The Bonneville plant has a magnesium salt capacity of 50,000 tons per year (MgO equivalent) (Kramer, 1997) but has only sporadically shipped $MgCl_2$. The most notable occasion was during the flooding at Great Salt Lake in 1983 and 1984 when the Bonneville plant shipped $MgCl_2$ to Magcorp (now U.S. Magnesium) to replace Magcorp's flooded $MgCl_2$ resource. The potash resource of the Great Salt Lake Desert is estimated to be 10 million tons of K_2O equivalent (Adams and Hite, 1983). Additional information on the potash resource of the Great Salt Lake Desert is contained in Nolan (1927) and Mason and Kipp (2002). Potash is used for plant fertilizer, as a flux in metal smelting, and as an ingredient in oil-well drilling fluid.

Paradox Basin

Bedded sylvite, carnallite, and associated subsurface brines underlie a large part of the Paradox basin in southeast Utah (fig. 8). The potash resource occurs within 18 of 29 evaporite cycles in the Pennsylvanian Paradox Formation of the Hermosa Group; eleven of these cycles contain significant amounts of potash (Hite, 1961). The potash resource of the Paradox basin is estimated to be 280 million tons K_2O equivalent (Adams and Hite, 1983). The salt occurs at shallow depth in salt anticlines within the basin (Elston and Shoemaker, 1963), but it is contorted there. Intrepid Potash – Moab LLC's Cane Creek mine (in the Cane Creek salt anticline) produced 534,993 tons of potash and halite in 2006 by solution mining within the old workings of this flooded underground mine (Phillips, 1975) in southern Grand County. Intrepid Potash – Moab LLC produces potash from an 11-foot-thick sylvite bed in the fifth evaporite cycle (down from the top of the evaporite sequence). This bed occurs at depths of less than 4000 feet (Hite, 1964). Process water for the operation comes from the Colorado River.

Sevier Lake

Sevier Lake, in south-central Millard County (fig. 8), dry through much of historical time, contains subsurface brines comparable to those of Great Salt Lake (Gwynn, 2006a), although Sevier Lake brines have a higher sulfate-to-chloride ratio and a lower magnesium content. In the mid 1980s, Crystal Peak Mineral Corporation built salt ponds and dikes, precipitated a salt floor, and produced some salt, but was unable to develop a profitable operation. The property reverted to the U.S. Bureau of Land Management.

Uinta Basin Sodium Carbonate Deposits

Halite and sodium carbonate minerals occur in the subsurface in the Tertiary Green River Formation sediments at two sites in the Uinta Basin of Duchesne and Uintah counties (fig. 8), the Duchesne deposit and the Bird's-nest aquifer. At the Duchesne deposit, core taken from a well at depths ranging from 4,165 – 4,252 feet contained three beds of mixed halite and wegscheiderite totaling 20 feet thick and six other beds of mixed sodium carbonate minerals: trona, nahcolite, wegscheiderite, and eitelite ranging in thickness from 0.3 - 1.5 feet (Dyni, 1996). The Bird's-nest aquifer contains sodium carbonate brine over at least a 250 square mile area (T. 8 -11 S., R. 22 - 25 E.) in the southeastern Uinta Basin (Dyni, 1996).

PERLITE AND PUMICE

Imerys' perlite processing facility is a 100,000-ton-per-year mill on a railroad siding in Beaver County (fig. 15). The facility opened in 1998 and passed from the Pearl Queen Perlite Corp. to Basin Perlite in December 1999, and to World Minerals (Harborlite is a subsidiary) in 2005. World Minerals was purchased by Imerys in 2005. The historic Pearl Queen mine supplied most of the ore to the plant from 1998 to 2004. The Pearl Queen's last reported production of 34,205 tons was for 2004.

The Pearl Queen deposit of northeast Beaver County, covers a 5,900-foot by 2,000-foot area, and ranges in thickness from 16 to 100 feet, averaging 80 feet. The ore is hosted by a 0.78 m.y. old obsidian-rich rhyolite flow. The rhyolite is vertically zoned with pumicious and shardy perlite on the surface, then granular perlite, then classical "onion skin" perlite. The majority of the ore has a fine granular texture. Pearl Queen has delineated (by drilling) a total resource of 25 million tons of ore with 4 million tons of proven reserves (Tripp, 2000).

World Minerals recently supplied the plant from the Black Springs mine. The Black Springs mine produced 11,081 tons in 2005 and 13,387 tons of perlite in 2006. Imery's Snowflake perlite property was inactive in 2005 and 2006. World Minerals closed the perlite facility and mine in 2006 to modify the mill. The World Minerals plant supplied perlite to U.S. Gypsum, to Midwest ceiling tile and construction businesses, and to the horticultural and foundry markets (North American Mineral News, 1999).

Figure 15. Imerys' Milford perlite plant, Beaver County, Utah.

PHOSPHATE

Most of the phosphate resource in Utah is contained in Permian rocks; a smaller resource is contained in Mississippian rocks (fig. 16) (Gere, 1964). The phosphatic shales of the intertongued Park City Formation and the Meade Peak Phosphatic Shale Member of the Phosphoria Formation of Permian age are the source of most of the phosphate production in Utah. Phosphate was mined for decades in the Crawford Mountains area of Cache County but was discontinued there in the 1970s and the center of production shifted to the southeast flank of the Uinta Mountains (fig. 16). In 2006, the only commercial operation is Simplot Phosphate LLC's Vernal mine (fig. 17) that mined 3,842,959 tons of ore to produce a concentrate in northern Uintah County. The company transports ore concentrates northward across the Uinta Mountains through a 90-mile-long, 10-inch diameter, underground, slurry pipeline to their Rock Springs, Wyoming fertilizer plant for treatment with sulfuric acid, which is a by-product from the oil and gas fields of the area, to manufacture fertilizer. Additionally, a small amount of low-iron phosphate is selectively mined for a pet food additive. A good recent summary of phosphate in the western U.S. is contained in Moyle and others (2001).

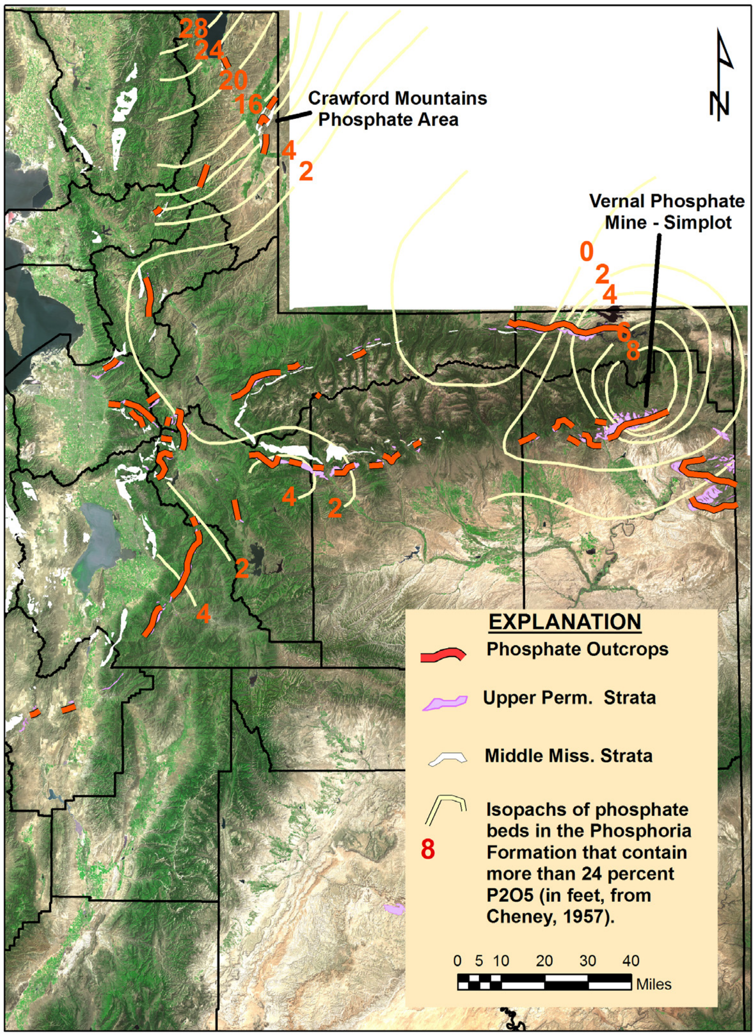

Figure 16. Phosphate resources of Utah.

Figure 17. Phosphate mining at the Vernal mine of Simplot Phosphates LLC on the south flank of the Uinta Mountains in Uintah County, Utah. The quarry floor is formed by two feet of clay on top of the Pennsylvanian/Permian Weber Sandstone. Dark material is phosphorite ore and the lighter material overlying that is overburden.

Mississippian phosphatic shales of the Delle Member of the Deseret Limestone and the Delle Phosphatic Member of the Little Flat Formation contain smaller phosphate resources throughout northern Utah that have not been exploited.

PORTLAND CEMENT

Utah contains vast amounts of the raw materials used for Portland cement production, including high-calcium limestone, natural cement rock, high-silica quartzite and sandstone, clay and shale, iron ore, and gypsum.

There are two current producers of Portland cement in Utah: Holcim, Inc. in central Morgan County and Ash Grove Cement Co. in eastern Juab County (Godek, 2003). Mountain Cement Co. uses the long defunct Lone Star cement plant in downtown Salt Lake City as a cement shipment terminal for production from their Laramie, Wyoming plant and from the Fernley, Nevada plant of Nevada Portland Cement.

Holcim uses limestone from the Jurassic Twin Creek Limestone, a natural cement rock which averages 42 percent CaO, at its 700,000 ton-per-year, dry-process Devil’s Slide plant. Holcim mined 902,317 tons of material at its plant in 2006. This plant (fig. 18), completed in November 1997, replaced their post-World War II-era 350,000 ton-per-year, wet-process plant (Holnam, Inc., 1999). Other materials utilized include: (1) high-calcium limestone from their Poverty Point pit in the Mississippian Great Blue Limestone of northeast Tooele County (18,860 tons in 2006), (2) silica from the Triassic-Jurassic Nugget Sandstone at their plant, (3) gypsum from the Jurassic Arapien Shale in eastern Juab County (six percent by weight of the finished cement is composed of gypsum), and (4) by-product iron from Kennecott Copper Corporation in western Salt Lake County (Holnam, Inc., 1999). Calcining and clinker formation occurs in a single 150-foot-long rotary kiln with a preheater/flash calciner. Fuel used at the Morgan County plant is primarily coal (with natural gas as a backup fuel). The plant also burns a small amount of shredded tires and cubed paper and plastic manufacturing waste from the Kimberley-Clark diaper plant in Ogden.

Figure 18. Holcim's Devil's Slide cement plant in Morgan County, Utah. The five-stage preheater/flash calciner tower is near the center of the photograph.

In 2004, Ash Grove mined 1,352,260 tons of Cambrian limestone and shale from a quarry adjacent to their dry-process, coal-fired Leamington plant (fig. 19); 38,736 tons of shale from the Mississippian Long Trail Shale Member of the Great Blue Limestone at their County Canyon quarry; and 108,724 tons of sandstone from the Permian Diamond Creek Sandstone at the company's Nielson quarry (Godek, 2003). The County Canyon and Nielson quarries are located within a few miles of Ash Grove's plant in eastern Juab County. In 2005 and 2006, Ash Grove began buying high aluminum clay from the Sand Wash 4 mine in western Beaver County. Ash Grove obtains iron from slag from Kennecott's copper smelter, and from mill scale from Nucor's steel recycling plant in eastern Box Elder County. Gypsum for retarding the setting time of the cement is probably obtained from the Jurassic Arapien Shale near Levan. To supplement coal as a primary fuel, Ash Grove burns a large number of whole tires. Ash Grove increased their plant capacity from 650,000 tons to 825,000 tons per year in the spring of 1996.

Figure 19. Ash Grove Cement's Leamington cement plant.

SAND AND GRAVEL

The bulk of sand and gravel production in Utah comes from Pleistocene Lake Bonneville shoreline deposits along the Wasatch Front urban corridor, from Provo in the south to Brigham City in the north (fig. 20). There are four major sand- and gravel-bearing Lake Bonneville benches or deposits that mark relatively long-lived, stable shorelines of the lake. The two highest benches, the Bonneville and Provo benches, provide most of the sand and gravel in the state. The Bonneville bench was deposited at an elevation of 5090 feet above mean sea level (Currey and others, 1984), nearly 900 feet above the current elevation of Great Salt Lake. The Provo bench was deposited at an elevation of 4,740 feet above mean sea level (Currey and others, 1984).

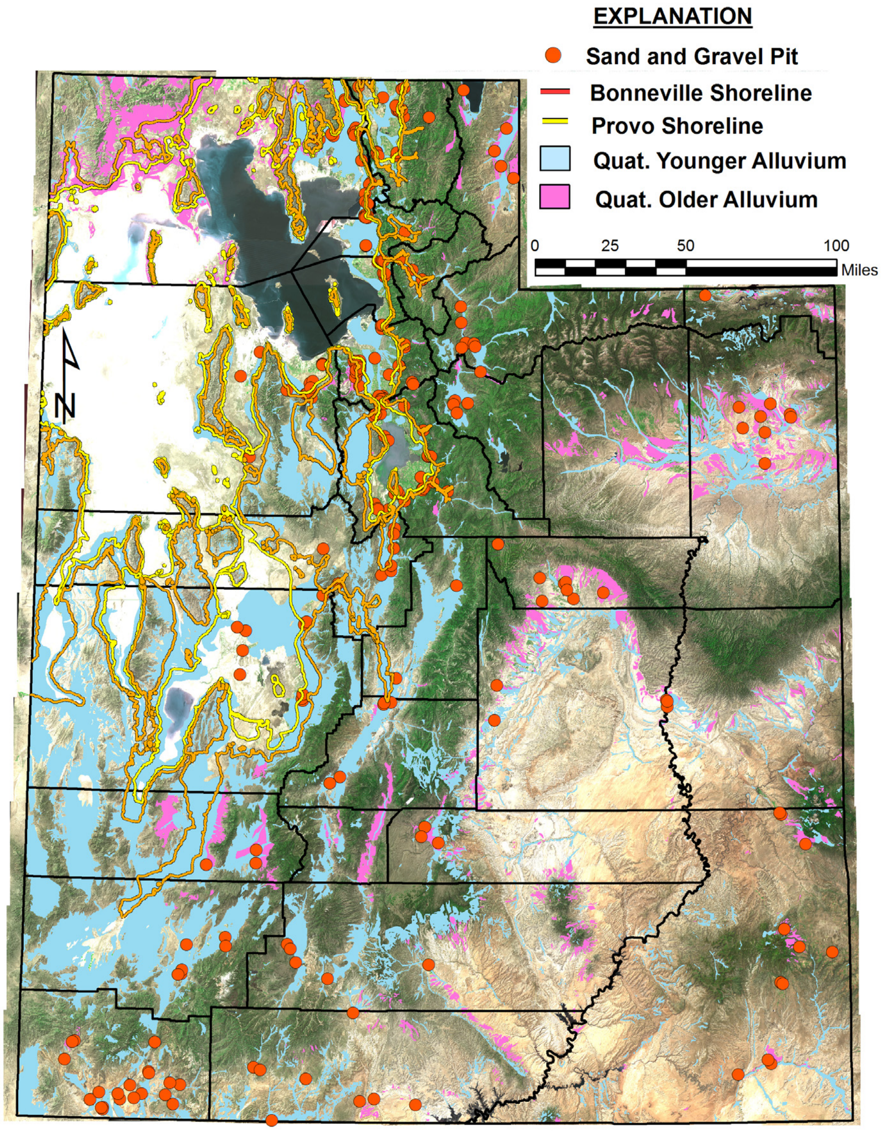

Figure 20. Sand and gravel resources and pits of Utah.

In 2005, 150 pits produced 33,900,000 tons of sand and gravel valued at $149 million (Bolen, 2007). Most of the production is for construction sand and gravel.

SILICA

McFarland and Hullinger (a subsidiary of Broken Arrow, Inc.) mined 74,213 tons of metallurgical-grade (+92 percent SiO_2) quartzite in 2006 from the Devonian Stansbury Formation in northeastern Tooele County at the SiO_2 1-6 pit, and sold it to Kennecott as a copper-smelting flux. The size of the reserves is not known, but is thought to be very large. Broken Arrow, Inc. mined 1000 tons of silica at their Tule Valley silica operation in Millard

County from the Ordovician Eureka Quartzite in 2005, but reported no production in 2006. Worthen/Williams LLC mined 7,551 tons of quartzite from the Devonian Stansbury Formation, in 2005, from the Roudabush 1 pit in eastern Tooele County for use in manufacture of siliceous refractories at their plant in Utah County.

SULFUR AND SULFURIC ACID

Although small natural sulfur deposits such as Sulphurdale in northeastern Beaver County have produced in the past (Mount, 1964), all of the current sulfur and sulfuric acid production is a by-product from industrial processes. Kennecott Utah Copper Company, located in eastern Salt Lake County, recovers about 1 million tons per year of sulfuric acid from smelting copper ore (Elise Erler, verbal communication, Kennecott Utah Copper Company, April 2000). The petroleum refineries in Salt Lake and Davis counties produce about 30 tons of sulfur a day. Most of the produced sulfuric acid and sulfur is sold to the fertilizer and chemical industries.

TITANIUM AND ZIRCONIUM

Dow and Batty (1961) describe 16 groups of Upper Cretaceous titanium/zirconium-bearing fossil placer deposits in Utah containing an estimated 1,043,000 tons of resource averaging 17.98 percent TiO_2, 5.67 percent ZrO_2, 20.98 percent Fe, and 0.09 percent $eThO_2$. These deposits occur near Emery, in the Henry Mountains, and in the Kaiparowits Plateau. Gloyn, Park, and Reeves (1997) report some newer, more detailed information for the Kaiparowits deposits. More than 14 titanium and zirconium deposits are distributed through the Cretaceous John Henry Member of the Straight Cliffs Formation in the Kaiparowits Plateau of Garfield and Kane counties (fig. 21). Development potential for these deposits was negatively affected by federal designation of the Grand Staircase – Escalante National Monument. Conversely a factor that might positively influence future development of titanium and zirconium deposits in the western U.S. is the recently announced construction of a 24-million-pound-capacity titanium sponge plant in north central Utah by Allegheny Technologies (2007). The plant will be located at the Rowley facility of U.S. Magnesium because magnesium metal is needed for titanium processing. Most of the magnesium metal can be recycled during this process. The plant is expected to begin operating in late 2008.

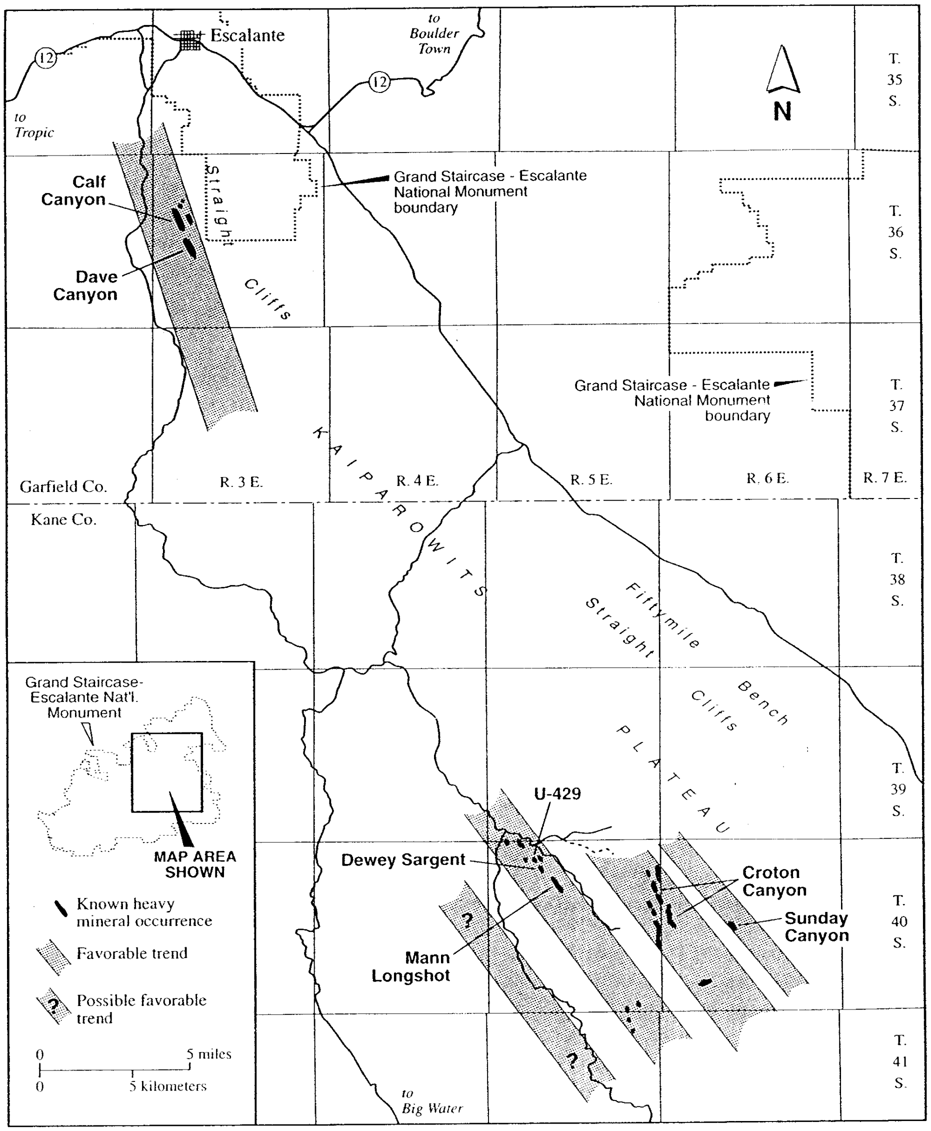

Figure 21. Titanium and zirconium deposits of southern Utah (from Gloyn, Park, and Reeves, 1997).

ZEOLITES

Fifty six zeolite deposits have been described in Utah, but seven large deposits currently seem to have the best chance of commercial development (fig. 22). Zeolite varieties found in these deposits are analcime, chabazite, clinoptilolite, heulandite, laumontite, mordenite, natrolite, phillipsite, stellerite, stilbite, and thomsonite (Mayes and Tripp, 1991). Through 2006 only the Mountain Green potassium clinoptilolite occurrence has been test mined on a small scale (Tripp and Mayes, 1990).

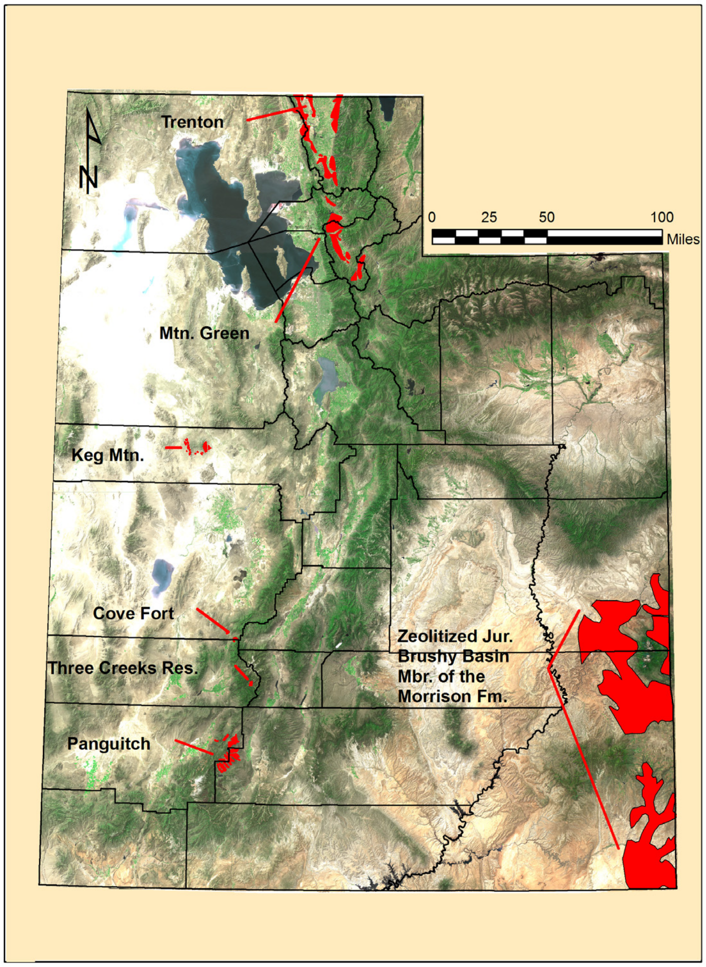

Figure 22. Zeolite deposits of Utah (modified from Mayes and Tripp, 1991).

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Session 2

Industrial Minerals,
Then, Now, and in the Future

A Short History on the Exploration for and Production of Chlorite in the Western United States

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ABSTRACT

The mention of chlorite mineralization typically conjures up a description of chloritization or chlorite alteration. Most Geologists are more familiar with alteration zones in which chlorite is part of greenschist facies alteration mineral suites, serpentinite complexes or commonly within chlorite schists associated with copper or gold deposits. However, in a few locations with unique conditions, low-iron, compact, microcrystalline high-purity chlorite is formed in economic concentrations that have been mined, marketed and sold into specialty applications which generally compete with talc or pyrophyllite mineral products.

In the western U.S., records of chlorite or talc-chlorite ore production start in 1927 in Nevada and later in the early 1940's in California. In these early days, the ores mined were sorted as talc, talc-chlorite and chlorite ores, with chlorite bringing nearly the same prices as the highest quality white talc ores in many cases. The "blue talc" ore, as chlorite was called in Esmeralda County, NV had prices that were set by the U.S. Office of Price Administration during World War II, along with the associated talc steatite ores. After the influence of wartime markets faded, prices and demand for the typically lower quality chlorite ores dropped and chlorite was mostly produced as a byproduct of associated talc production. Production from the Nevada mines ceased in the early 1970's and the production from the Talc City, California District concluded in the early 1980's. Production of chlinochlore chlorite was then taken up by the Antler Mine in Montana, which started production in 1976 and operated until 1999.

The parent rocks for the chlorite ores or "green talc" in the Talc City, California and Palmetto/Sylvania Districts in Nevada were mostly aluminous lithologies within dolomite units or felsic igneous rocks in contact with dolomites. In Montana, the chlorite ore is the direct replacement of biotite gneiss. In all cases, the introduction of magnesium-rich fluids and the exchange of silica between bounding lithologies was necessary to produce the chlorite ores, and commonly both chlorite and talc are present to some degree.

Early markets for chlorite and chloritic ores were similar to the early product applications for talc, but much of the chlorite was sold specifically for ceramic kiln furniture, roofing and insecticides. In recent years, chlorite has continued to be preferred over talc in a number of market applications such as cordierite body ceramics and water-based paint applications.

Exploration for new chlorite resources primarily focuses on feldspar-replacement alteration models within Precambrian gneisses, felsic igneous rocks or aplites in regions where magnesium-rich metasomatic fluids are known to have been a component of regional geologic processes. The dike or vein-like nature of most of the known occurrences limits the size potential of the deposits and thus the size of the markets any chlorite production could support.

INTRODUCTION

The chlorite group of minerals are phyllosilicates all with similar chemical, crystallographic and physical properties. Specific light-colored varieties of chlorite have been mined and marketed as a talc-like mineral from a select number of mining districts within the western United States over the past 80 years. In many locations, chlorite is associated with or interlayered within talc deposits. Chloritization as seen in propylitic alteration zones around sulfide deposits or chlorite schists do not typically develop the purity and quality chlorite required for fine ground products.

CHLORITE MINERALOGY

The name chlorite is derived from a Greek word for *green*, alluding to the common color of the mineral. The hypothetical formula for chlorite with an interlayered structure with alternating talc and brucite layers is:

$$Mg_3(Si_4O_{10})(OH)_2 + Mg_3(OH)_6$$

However, in most chlorites, Al, Fe^{2+} and Fe^{3+} substitute for the Mg in both the talc and brucite sheets, and Al can also substitute for Si in the tetrahedral sites (Hurlbut and Klein, 1977). Minor substitution in chlorite is also common with Mn, Cr, Ni and Ti being the typical elements substituted (Deer, et.al., 1966). The varieties of chlorite differ from each other in the amount of substitution and the manner in which successive octahedral and tetrahedral layers vary along the c-axis. Chlorites are primarily described by their composition within three parameters: ferric iron, silicon and total iron. The principle members of the group are chlinochlore, penninite and prochlorite. Chlorite usually displays a massive foliated habit or is seen in aggregates of minute scales (Hurlbut and Klein, 1977). However, in most economic chlorite deposits, the mineral is typically described as compact or microcrystalline.

Chlorite is a common mineral in metamorphic rocks, and specifically within greenschist facies rocks in which they are the diagnostic mineral. These minerals are commonly formed as the result of the alteration of primary ferromagnesian minerals. Chlorite also forms within igneous rocks as a retrograde alteration product of pyroxene, amphibole, biotite and garnet. The green color of many altered or metamorphic rocks is the result of the presence of chlorite.

Chlorite is commonly present within most high quality talc ores typically in amounts ranging from 0 -5%. Darker green bands within talc ores are most likely chlorite and are common within massive or even schistose ores. Some mine locations such as Trimouns, France and Rabenwald, Austria have significant chlorite production resulting from footwall ores that have been derived from schists and may contain more than 70% chlorite with the remainder talc (Harben and Kužvart, 1996). In most cases the chlorite in these types of deposits is darker in color and not utilized for applications that require white mineral powders. A number of economic chlorite deposits have formed as the replacement of feldspars within gneisses, granitic rock or from felsic dikes.

HISTORIC PRODUCTION

The first mineral claims for talc or chlorite were staked in 1927 in the area of the future Oasis Mine in the Sylvania district in Nevada. Mining appears to have begun in Esmeralda County, Nevada in the Sylvania District in the year 1928, but production from the District was not officially reported until 1940. The peak of discovery and production in the Palmetto/Sylvania area was in the early 1940's at least partially in response to the increasing demand for steatite talc for use in wartime electronic insulator applications. The Sierra Talc & Clay Company entered the District by buying the Oasis Mine in 1938 and operated there continuously until 1966. Sierra Talc or its successor, Cyprus Industrial Minerals, also purchased the Roseamelia Mine in 1938 and the Reed Mine in 1952. Cyprus controlled the Oasis Mine property until at least 1986 and had a lease on the Lida / Fair Lady claims as recently as 1993. Insignificant chlorite production occurred within the two Districts from the only 6 mines operating in early 1970's (Papke, 1975).

The Frisco Mine in the Talc City District was on a State lease in California, and was first leased by the Sierra Talc & Clay Company in 1942. The property was later assigned to Cyprus Industrial Minerals and was operated first as an underground mine and was later exploited through an open pit. By the last 1950's, mine development of the Frisco included two inclined shafts and three surface pits, the largest of which was 350 feet long, 100 feet wide and 50 feet deep. Production in the late 1970's approached 4,000 tons per year, but by around 1980 production was down to approximately 3,000 tons per year of chlorite. The mine was reclaimed and quitclaimed back to the State of California by Cyprus in 1982.

Production for Cyprus Industrial Minerals was taken up by the Antler Mine in Montana, which was able to generate the required quantities of chlorite ore after 1978. The Antler Mine remained the sole source of chlorite ore for Cyprus Industrial Minerals and their predecessor, Luzenac America, until 2002, when the final stockpiles produced at the end of mining in 1999 were depleted. Since 2002, all chlorite requirements for North America have been supplied by imported Chinese crude.

EARLY CHLORITE MARKETS

Ores from this region were known to have been used in ceramic applications, specifically in kiln furniture which needed to be able to withstand repeated firing and cooling cycles. It is likely that much of the chlorite ores were also used in asphalt roofing applications, in insecticide products to provide an inert bulk filler to the dusting powders and in joint cement compounds for drywall applications during the same time. Most of the larger talc and chlorite mines in Nevada and California were controlled by the processing and marketing companies during the early to mid-1900's, although many of the small mines were individually operated and sold crude ore to the processors in the region. Much of the milling at the time was done at operations in a number of locations in southern California (Zurich, Victorville, Keeler, Baker, Cartago and Los Angeles) and they typically utilized roller mills to produce 200 to 325 mesh powder products.

The chlorite from the Frisco mine basically produced two grades of ore, Pyrotalc and Sierralite. The Pyrotalc brand was considered the low-grade ore and was primarily utilized as an insecticide carrier. The higher grades of ore were mined and sorted and sold as Sierralite, which was commonly blended with clays and used to make cordierite body ceramics for sanitary ware and kiln furniture. In the years around 1950, the chlorite ores from the Talc City area were hauled to Keeler and ground into finished chlorite products (Ellsworth, 1951).

THE NEVADA DEPOSITS

Most of the talc and chlorite deposits in Nevada are located in the Palmetto and Sylvania districts in Esmeralda County (Papke, 1975). Up until the 1970's, these districts and Talc City in

California were the only locations that had produced chlorite ore in the western United States. Over 300,000 tons of talc and chlorite ores were produced from these two districts in Nevada with less than 20% of that tonnage as primary chlorite ore. It was common in Esmeralda County to call the chlorite, "blue talc", even though it was neither (Papke, 1975). Although these deposits are situated proximal to Inyo County in California, they are neither contiguous with nor similar to the talc and chlorite deposits in the Inyo Mountains or Talc City in that county (Berg, 1995). The geology of the deposits in the Palmetto District and those in the Sylvania District are also dissimilar from each other (Papke, 1975).

In what Papke defines as the Palmetto District, the largest chlorite producer was probably the Lida Mine (later the Fair Lady Mine) which produced at least 1,000 tons of talc and chlorite ore during the 1940's and later during a second phase of activity in the 1960's. The second largest producer was the Ace in the Hole Mine, which operated in the 1960's, but produced only 600 tons of chlorite ore.

In the Sylvania District, the largest chlorite producer was likely the White King Extension which produced up to 23,000 tons of chlorite ore during the 1950's and 1960's. Many mines in this district produced minor amounts of chlorite or had chlorite-talc mixture ores as part of their production. The second largest producer was the Lone Springs Mine, which had total production of around 7,000 tons of chlorite, mostly in the 1950's.

The Lida or Fair Lady Mine in the Palmetto District was mined primarily for talc prior to 1942, but there were common occurrences of chlorite noted throughout the camp (table 1.). In the mid-1960's exploration drilling was completed by Huntley Industrial Minerals, Inc. as part of their evaluation of the chlorite potential. The potential ore on the claims was defined as a "high-alumina talc" within a large lenticular zone 300 feet long and 130 feet wide, and appeared to be entirely contained within the host dolomite. Resources of around 100,000 tons were defined by Huntley with the chlorite was described as mostly greenish gray to olive gray. Huntley never developed these resources.

Table 1. Chemistry and Mineralogy of the Lida/Fair Lady Mine.

	SiO_2	Fe_2O_3	Al_2O_3	MgO	LOI	GEB
1	34.8%	2.8%	24.6%	24.4%	12.1%	81
2	38.1%	4.5%	22.5%	32.5%	12.3%	79.4
3	Chlorite	Talc	Dolomite/Calcite	Mica/Quartz	Rutile	
	97%	1%	None	0.7%	1%	

[1] Chemistry of the Fair Lady/Lida Mine, Nevada (Nelson, 1967).
[2] Chemistry of the Fair Lady Chlorite (Clark and Radcliffe, 1991).
[3] Typical mineralogy of chlorite from the Fair Lady Mine (Clark and Radcliffe, 1991).

Geology

There are two varieties of chlorite mineralization developed within the Palmetto District. The central or main part of the District contains mostly talc deposits which are within the Harklin and Poleta Formations of early Cambrian age. Talc typically replaces portions of the associated carbonates, quartzites and hornfels in these Formations. The chlorite deposits are concentrated in areas to the northwest or east of the main District.

To the northwest, several occurrences are located in jointed and faulted quartz monzonite porphyry. Mineralization appears to primarily be associated with and controlled by regional faults that parallel the major drainages. The Ace in the Hole Mine here represents this type of deposit, but is a small occurrence and produced only 600 tons during its life.

To the east of the main Palmetto District, the Lida Mine lies somewhat by itself and contains a unique and separate type of chlorite mineralization. Although the Lida was mined primarily for talc, significant chlorite mineralization is present in the lower part of the Precambrian Deep Spring Formation on the south side of the property. Chlorite mineralization appears to be stratigraphically controlled and has replaced primarily mudstone and quartzite beds within the middle unit of the Deep Spring Fm. Fine-grained quartz diorite dikes are closely associated with much of the chlorite mineralization and show sharp contacts between the two rock types. Some fault control of mineralization occurs, but the chlorite is mostly stratigraphically controlled by the mudstones within the carbonate section (Nelson, 1967).

In the Sylvania District, the sedimentary host rocks are predominantly the Precambrian Reed Dolomite and to a minor extent the Precambrian Wyman Formation. Granitic rocks of Jurassic age are abundant in the region and are separated from the Reed Dolomite by a regional thrust fault zone in the main part of the District. The quartz monzonite can be commonly seen overlying the Reed Dolomite (fig. 1). Most of the significant talc and chlorite deposits in this district occur along this fault zone (Papke, 1975). The chlorite mineralization occurs as replacement of the quartz monzonite porphyry along the fault contact and into the porphyry (fig. 2). The chlorite commonly occurs without significant associated talc, but talc can be present as the replacement of the underlying Reed Dolomite. The most significant chlorite deposits and the largest chlorite mining operations were located where the fault contact between these two units was steeply dipping.

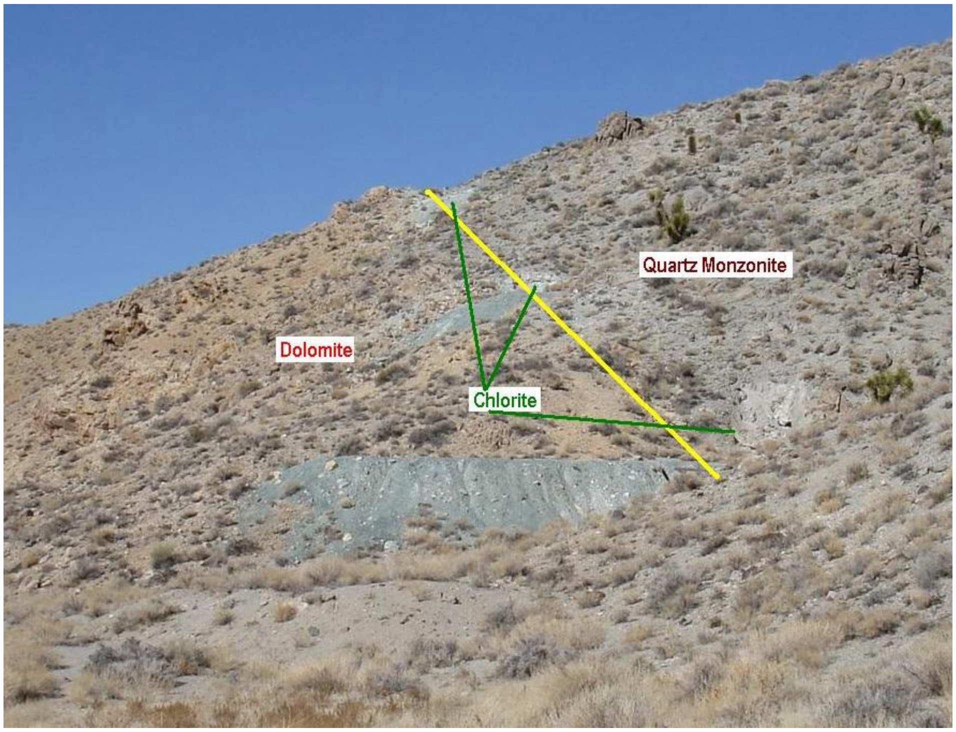

Figure 1. Sylvania District. Chlorite mineralization along thrust contact between quartz monzonite porphyry and Reed Dolomite.

Figure 2. Sylvania District. Chlorite metasomatism replacing altered quartz monzonite.

Numerous notations within internal company reports indicate that chlorite mineralization in both the Sylvania and Palmetto Districts was commonly associated with quartz monzonites or granite porphyries, and their contact with diorite dikes. Occasionally there is dolomite reported near the contact of the units, but in at least one report it was noted that dark green chlorite was present along the contact and that the mineralization preferred the granite (internal communication, 1941).

THE CALIFORNIA DEPOSITS

The principle chlorite source in California was the Frisco Mine in the Talc City area about 6 miles northwest of Darwin. The old workings of the mine were developed prior to 1942 and produced a “green talc” with greater than 20% alumina, apparently chlorite and occasionally also called pyropyllite. The mining of chlorite at the Frisco Mine by Sierra Talc & Clay Company was resumed in 1946 and the mineral product was sold under the name “Sierralite” for use in cordierite ceramic bodies (Page, 1951). In the 1950’s the mine was commonly referred to by the Sierra Talc & Clay Company as the Sierralite-Pyrotalc Mine.

Geology

In the Talc City area, a number of chlorite-rich deposits have been exploited. A regional granite within 1 km of this district is likely responsible for the metasomatism and mineralization of the aluminous units. Limestones in the area were replaced by dolomite, which were later silicified and subsequently flooded with MgO, forming most of the talc here. Diabase and felsite dikes commonly cut the Paleozoic carbonates in the Talc City District as well as some of the granitic rock, and are commonly the host for the chlorite deposits (Page, 1951).

Dikes of a pale-colored, fine-grained felsite are found near the mine and have been subjected to chlorite alteration (table 2). The massive green chlorite in the deposit occurs abundantly as the replacement of these felsic dikes (Table 3.), adjacent to the Paleozoic dolomite and limestone of the Pogonip Group and siliceous hydrothermal rocks that are most commonly replaced by talc (fig. 3). The principle ore zones consist of semi-parallel, steeply dipping dark green chlorite “veins” from 1-14 feet thick, striking generally northwest and dipping 40-50° to the northeast with spacings of 5-30 feet, but several other minor chlorite shear zones are present at different orientations (Hall and MacKevett, 1958).

Table 2. Chemistry of the Frisco Mine, chlorite ore for Sierralite (Page, 1951)

SiO_2	Fe_2O_3	Al_2O_3	MgO	CaO	LOI
36.24%	1.19%	23.56%	23.39%	1.47%	12.19%

Table 3. Typical mineralogy of chlorite from the Frisco Mine.

Chlorite	Talc	Dolomite/Calcite	Mica/Quartz	GEB
97%	Trace	2%	<1%	75-78

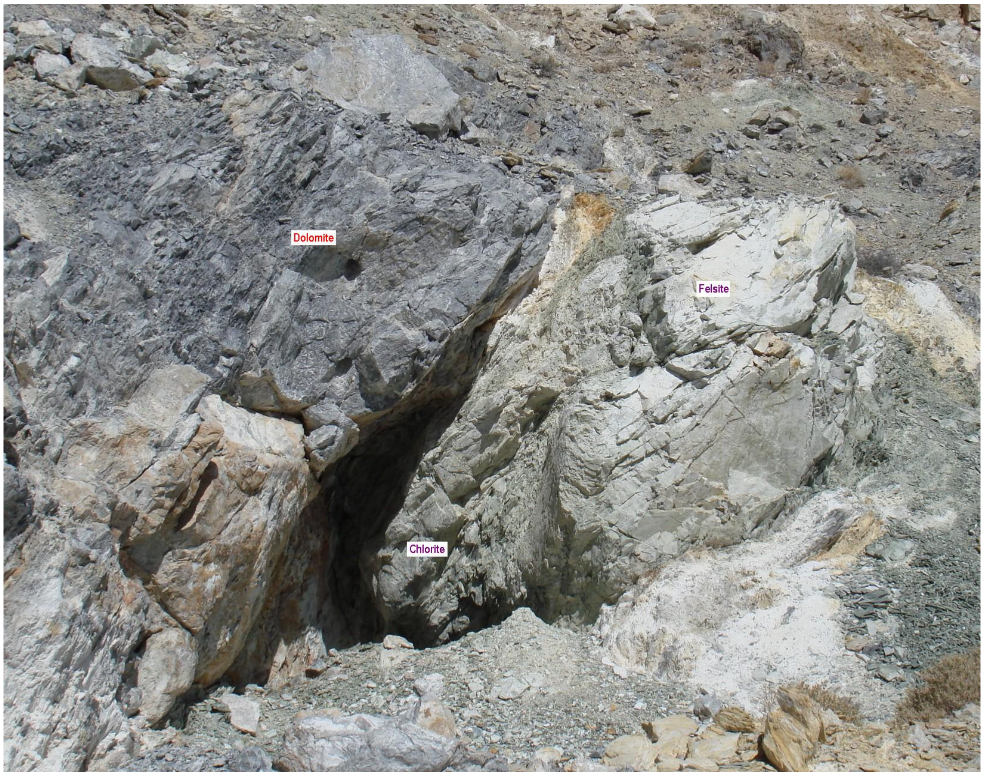

Figure 3. Frisco Mine. Felsite with significant replacement by chlorite, in sharp contact with dolomite.

Although the ore was relatively consistent at the Frisco Mine, occasionally quality control issues surfaced and were typically related to unusual levels of either mica or potassium. The mica impacted the shrinkage factor, lowered thermal shock resistance and reduced absorption in cordierite bodies. Mica levels of up to 10% would double shrinkage to 10% and absorption would drop from 13% to less than 3%. Typically CaO + K_2O would have been >0.2% in the ore and greater levels would negatively impact linear thermal expansion.

THE MONTANA DEPOSITS

The Antler ore body near Silver Star, Montana was identified in 1975 and went into production on a small scale the following year. The clinochlore chlorite veins within the deposit were formed within Precambrian gneisses on the southeast flank of the Highland Mountains in southwestern Montana. These Archean age gneisses were metasomatised along a north-northwest trending fault system during a Proterozoic event that sent magnesium-rich fluids along the steeply inclined faults. At the Antler Mine, the set of three parallel veins were limited and terminated abruptly in all three dimensions. At the greatest extent they were 300 feet vertically, 500 feet long and 25-30 feet thick at their widest dimension. All of the veins pinched out to the bottom and to the north within the confines of the pit. Only the south end of the central vein extended beyond the limits of the pit to the south.

Geology

The presence of chlorite within the gneiss is a result of fault-controlled metasomatism (fig. 4). This replacement of quartzofeldspathic gneiss by chlorite by the addition of magnesium and loss of silica, sodium, calcium and potassium is an atypical type of chlorite deposit in this region and seen in Montana only at the Antler and the Grandview properties (table 4) (Berg, 1979). Residual zircon and rutile within the chlorite further indicates that the host rock was likely a biotite-quartz-feldspar gneiss. The chlorite mineralization at Antler is younger than the amphibolite facies metamorphism of the Precambrian basement and is also younger than the cross-cutting late Proterozoic mafic dikes exposed in the pit.

Figure 4. Antler Mine. Chlorite metasomatic replacement of altered biotite gneiss.

The chlorite veins are bounded by a pale green quartz-sericite-chlorite zone. Propylitic alteration of the gneiss was noted adjacent to the quartz-sericite-chlorite horizon (Berg, 1979). The Antler deposit is within 2 miles of both the Hell Canyon pluton to the southwest and the Rader Creek pluton to the northeast, which both could have contributed to the hydrothermal waters which formed the mineralization. All other minor occurrences of chlorite replacement of gneisses in the Highland Mountains are associated with major northwest trending structures and are typically iron-rich, small and highly fractured.

Table 4. Chemistry of Antler chlorite (Berg and Crouse, 1999)

SiO_2	Fe_2O_3	Al_2O_3	MgO	LOI
32%%	<5%	22%	30%	12%

Although the dry ground GEB (General Electric Brightness) of the Antler chlorite was almost identical to the Lida/Fair Lady chlorite, the fired color of the Fair Lady ore exceeded the brightness of the fired Antler ore by over 10 points.

Minor chlorite production has also occurred from a number of small prospects at the south end of the Ruby Mountains, west of Dillon, Montana. In a number of locations, chlorite has replaced light-colored felsite dikes within Precambrian metasediments. The mineralization appears to be discontinuous, narrow and incomplete in most locations.

CURRENT CHLORITE PRODUCTION AND MARKETS

With the closure of the Antler Chlorite Mine in Montana, the North American market began to rely upon import lump crude chlorite from Liaoning Province in China. Shipments of this crude now supply all requirements in North America.

Over the years, the one market area that has continued to rely upon chlorite products is the cordierite body ceramic application area. This market continues to be an important market for chlorite today.

Water-based paint applications are also one of the core chlorite product applications. As a result of regulations restricting VOC (volatile organic compounds) in many industrial manufacturing and consumer products, oil-based paints formulations which favored talc have been to a large degree replaced by water-based formulations which may utilize talc, but commonly favor chlorite due to its hydrophilic nature. Because of its acid resistant character, chlorite performs well in primers and corrosion resistant paints. Chlorite also produces better flatting and higher opacity than ground calcium carbonate in paint applications (Berg and Crouse, 1999).

CHLORITE EXPLORATION

Further exploration for low-iron, compact, microcrystalline chlorite resources will likely need to focus on geologic domains that contain feldspar-rich host rocks that have been subject to low-grade magnesium enrichment and silica removal along significant regional fault zones. The gneiss replacement model has the best potential for resource size, but appears to be rare in nature or uncommonly exposed a surface. Replacement of diabase or mafic dikes with chlorite is relatively common, but produces a dark, contaminated potential ore that does not have significant market value. The replacement of light-colored feldspar-rich dikes such as aplite or felsite can produce a high quality chlorite ore, but this style of mineralization is typically small in size. In some locations, such as in Liaoning, significant chlorite resources are associated with carbonate-hosted talc deposits and develop in the aluminous contact formations. If these adjacent units are low in iron and high in alumina, a high quality chlorite deposit can form as the result of an over saturation of magnesium. More common than not, the chlorites associated with talc deposits can be high in iron and not very useful in the white chlorite powder market applications.

CONCLUSIONS

To most Geologists, chlorite is gangue, a nuisance, and a low-grade metamorphic mineral. To some of the customers of Rio Tinto Minerals, who supplies chlorite powders to the marketplace, chlorite solves their mineral product requirements better than any other mineral. I hope that there is always a place for niche minerals like chlorite and people to promote the exploration, production and marketing of such unique minerals.

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A History of Stone Resources in Canada as a Primer for Stone and Aggregate Resource Planning in Alberta

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ABSTRACT

If building stone and construction aggregate are viewed as an intimate mixture of materials with overlapping uses, a four-hundred year Canadian history can be woven that demonstrates on-going principles and paradigm shifts; information that is helpful in designing stone resource evaluation and mapping plans for Alberta.

The use of stone as a construction material was encouraged by civic leaders in Quebec City (1682), Montreal (1852), Saint John (1877) and Calgary (1886) after devastating fires spread through wooden buildings. The switch in fundamental building material was sometimes dramatic and presented economic opportunity; four years after the Calgary fire over 50% of Calgary's tradesmen were working in the sandstone industry and fifteen quarries were operating around Calgary. One key in the development of a regional building stone industry was a local source of supply. The source rock is evident by simply looking at the older buildings in every major Canadian city. Capability for water and rail transportation was another major consideration, especially for export to other regions. The first use of British Columbia building stone (Gabriola Island sandstone) was as an export (San Francisco Treasury Building, 1837) and the most recognizable rock from the Canadian Maritimes (Wallace sandstone) is seen in New York's famous brownstone houses and the bridges of Central Park. Around the start of the 20th century the introduction of concrete for building foundations in Alberta, followed by the use of steel for the structural framework of buildings and gravel for roads spelled the end of the Sandstone Era and the start of the gravel age. Sand and gravel production in Alberta exploded from about 192 thousand tons in 1946 to about 31.5 million tons in 1970 due to massive road construction. Alberta still obtains 99% of its aggregate from surficial sources but the first dedicated crushed stone aggregate quarry started operating in 2006; this is the start of a paradigm shift back to stone.

We should evaluate the magnitude and rate of the shift to crushed stone through a comprehensive market and demand analysis and review our transportation options. We should then evaluate the near-surface bedrock formations for a spectrum of potential stone resource uses including building stone. Study should begin closest to the areas of predicted demand and along the transportation routes to these areas and dedicate itself to areas where development is feasible. If potential is established these areas should be flagged for resource use and monitored for land uses that restrict development.

INTRODUCTION

Building stone and construction aggregate can have the same geological source and are considered in this paper as an intimate mixture of materials with overlapping uses that span a period of about 400 hundred years in Canada. Information and stories about building stone are broadly appealing and effective for public education especially when linked to history and architecture. Stone as seen in heritage buildings is a valuable tool for relating societal needs and resource use and for explaining local and regional geology. The author has successfully delivered numerous ‘rock walks’ (building stone tours) to a wide variety of groups in both Edmonton and Calgary (Edwards, 2007). A basic understanding of building stone in Canada and Alberta is helping the author identify a number of basic principles and paradigm shifts relevant for planning geological activities, predicting potential economic growth and confirming the need for resource management in Alberta. This paper summarizes the stone history of Canada and Alberta and uses it as background in recommending future activities of the Alberta Geological Survey.

HISTORY OF STONE

Canada

After a fire in Quebec City in 1682 the use of stone as a construction material for houses was encouraged. The first stone used was found in the heart of the city at Cap Diamant and was known as cap stone or Quebec stone. Quarry workers nicknamed it ‘stinking stone’ because of the odour of methane and sulphur released when the stone was crushed. This shale was a poor quality building stone but readily exploitable and very low cost. Maison Cureux is a rare example of a surviving house constructed from cap stone. It was destroyed in 1709 by the French government to make way for fortifications but reconstructed in 1729 at the demand of residents (Côté et al, 2005). In Montreal the local stone was Trenton limestone and the oldest remaining building is the Saint-Sulpice Seminary (1684-1687) (Archiseek, 2007).

This story of fire and devastation in wooden structures giving rise to renewal and permanence in the form of stone is repeated across Canada and through the ages. The use of stone as a construction material was not only a public safety measure, it was a sound investment strategy encouraged by civic leaders. Starting with the Quebec City Lower Town fire in 1682 (Côté et al, 2005), major fires are recorded at Montreal in 1721 and 1852 (Montreal History Links, 2007), Saint John New Brunswick in 1877 (Saint John, 2007), Calgary in 1886 (City of Calgary, 2006), St. John's Newfoundland in 1892, Hull-Ottawa in 1900, Toronto in 1904 and even in the Canadian Parliament itself (the original Centre Block of the Parliament Buildings in Ottawa was destroyed by fire on 1916) (Wikipedia, 2007).

Newfoundland was discovered in 1497 so you would think that it should have the longest and greatest stone use but St. John's has a preponderance of wooden houses. During the 16th and early 17th centuries fishermen and officials returned to their homeland for the winter so houses were designed for shelter rather than permanent habituation and it was not until 1811 that the erection of permanent dwellings was tolerated (Murphy, 1982). Even so there is a record of local dimension stone usage; it traces its roots to the English-French hostilities of the 17th and 18th centuries. Sandstone from the St. John’s area and limestone from Conception Bay were used by the English in the construction and maintenance of fortifications around St. John’s including Fort

William (1618-1779), Fort Amherst (1777) and Fort Townshend (1779-1871) (Newfoundland and Labrador, 2007).

Across the country great impetus was given to the quarrying industry by the construction of fortresses. The building of fortifications started at Quebec City in 1621 with Fort St. Louis under the French regime and continued after about 1740 with the British. Demand for stone led to a diversification of sources including Cap-Rouge and Ange-Gardien sandstone and Beauport and Deschambault limestone (fig. 1) (Côté et al, 2005). The building stone industry in Ontario got a vigorous start with demand for stone for fortifications for the War of 1812 (Ontario, 2007). In Manitoba Tyndall Stone was first used in the construction of Lower Fort Garry in 1832 (fig. 1) (Manitoba, 2007). Construction of fortresses and projects such as the Rideau and Welland canals (1824 to 1831) were megaprojects that required huge amounts of stone (Ontario, 2007). They resulted in quarry development and attracted skilled labour; these in turn started stone industries in some regions. Deschambault, Queenston and Tyndall limestones were first quarried in the early 1800s and are still being produced (fig. 1) (Ledoux and Jacob, 2003; Ontario, 2007).

Figure 1. Historically significant building stone in Canada. The numbers of quarries identified for each province were active in 2006 (after Panagapko, 2007).

The 1800s and early 1900s were the heyday of the Canadian stone industry for local use and international trade. The first building stone to be quarried on the west coast was probably sandstone from Gabriola Island that was shipped to San Francisco for use in the Treasury Building in 1837. Late Cretaceous age sandstone was quarried from many islands and extensively used in buildings throughout British Columbia. By the 1920s the Gulf Island sandstone was replaced by Haddington Island Andesite (fig. 1) (Hora and Miller, 1994). This uniform, workable and erosion resistant volcanic rock formed 5 to 8 million years ago from an eruption along North Vancouver Island (Mustard et al, 2003). Gray granodiorite was quarried from islands north of Vancouver and these Coastal granites formed the foundation material for most large buildings in Vancouver and Victoria after the 1880s (fig. 1) (Hora and Miller, 1994).

Queenston limestone (Silurian Lockport - Amabel Formation) is a pearl-grey dolostone altering to brownish-buff with pink calcite crinoid stalks (Côté et al, 2005). It has been quarried for about two centuries along and behind the Niagara Escarpment from the Bruce Peninsula to Niagara Falls. Queenston limestone is found in buildings in southern Ontario, Quebec and the Maritimes and is still a major building stone (fig. 1) (Ontario, 2007).

Dozens of quarries operated between 1800 and 1940 in Nova Scotia (Brown et al, 1986) and between 1855 and about 1910 millions of tons of granite and sandstone were exported from New Brunswick throughout eastern North America (New Brunswick, 2007). The longest operating and important granite quarries in the region were at Hampstead and St. George in New Brunswick and Shelburne and Halifax in Nova Scotia. Many major towns and cities in New England, Ontario and the Maritimes have older buildings or monuments decorated by pillars or columns of St. George granite (Fensome and Williams, 2001).

Over two hundred public and private buildings throughout the Maritimes reflect the beauty and diversity of the local Carboniferous to Permian age sandstone. Red and brown Wallace sandstone was used in Province House (1843) in Charlottetown P.E.I, the site of the 1864 conference that led to Canadian confederation (Fensome and Williams, 2001). Wallace sandstone was widely used throughout the Maritimes, Ontario and Quebec and was the replacement rock for Ohio Sandstone in the Federal Parliament Buildings (Lawrence, 2001) and for Credit Valley Sandstone in the Ontario Parliament Buildings (fig. 1) (Freeman, 2003). If you watch major movies you often see New York's famous brownstone houses and the bridges of Central Park. The brownstone of Boston, Providence, Philadelphia and New York is olive to tan Maritime or Wallace sandstone and was coveted by American builders (Fensome and Williams, 2001).

These examples of early building stone demonstrate that transportation was a critical element. Stone was either quarried close to the market to minimize transportation or the stone was shipped by water, the least costly mode. The development of the Canadian rail system, ultimately into a transcontinental rail network, created some fundamental changes in the stone industry. Like fortresses and canals the railways were major projects unto themselves. Stone quarried along the right of way was used for bridge piers, building foundations and markers. Geologists joined the surveying expeditions of the Canadian Pacific Railroad in the Canadian Cordillera in the 1860s to locate dimension stone sites (Hora and Miller, 1994) and the earliest granite quarrying in northern Ontario was done for the construction of the CPR (Ontario, 2007).

Inevitably quarrying of stone for railway construction was followed by the use of the stone for buildings and monuments (Hora and Miller, 1994) and the rail systems greatly enhanced the ability to market and distribute stone. The opening of a railway in 1875 in the Quebec City region meant that Rivière-à-Pierre granite could be mined and distributed further afield. The piers of the Quebec Bridge were carved from Rivière-à-Pierre granite as was the pedestal for the Statue of Liberty in New York City (Bergeron et al, 2001). In Newfoundland granite was quarried for trestle abutments for a narrow gauge railway (1898) and after construction was shipped on railway flatcars to St. John's for building the railway station and paving Water Street with cobbles (Newfoundland and Labrador, 2007). Coastal granite from the west coast made it as far as Edmonton for use as the foundation of Alberta's Legislative Building in 1909 (Burwash et al, 2002) and granite from Ignace Ontario was used for the steps and floor surfaces of the Manitoba Legislative Building (1913-1920) (Brisbin et al, 2005).

Development of the national rail system in the last quarter of the 19th century meant greater access by architects and builders, especially in interior Canada, to high quality national stone and later to exotic offshore stone, particularly as polished cladding or interior finishes. Stanstead Grey granite, a medium to coarsely crystalline, light to silver grey granite of Devonian age, was commonly used for floorings and facings throughout Canada during the 1920s to 1930s and can be seen from Alberta across to the Maritimes and in the northeastern United States (fig. 1). It has been mined for about 125 years in the Stanstead area, near the Quebec-Vermont border. Missisquoi marble of Cambrian age graces the interiors of many provincial parliament buildings. Missisquoi stone is quarried in the Philipsburg area of Quebec (fig. 1) (Ledoux and Jacob, 2003; Burwash et al, 2002).

Tyndall Stone is Canada's most recognizable stone (fig. 1). It is a light grey to cream coloured limestone with a buff network of dolomite mottlings (fossil worm or shrimp burrows) and contains highly visible sunflower corals, horn corals, gastropods, and cephalopods. When television viewers tune into the national news from the interior of the Canadian Parliament Buildings in Ottawa the tapestry stone they see in the background is Tyndall Stone (Gillis Quarries Ltd., 2007). Tyndall Stone is used across the continent and in buildings in every major Canadian city, for example, the Empress Hotel main lobby addition in Victoria (1992-93), Terminal City Club Centre in Vancouver (1998), the Canadian Bank of Commerce (now CIBC) in Edmonton (1929), the Canadian Museum of Civilization in Hull (1989), Le Château Apartments in Montreal (1924-26), in the Lied Centre for the Performing Arts in Omaha (1990) and the Walsh Centre for the Performing Arts on the Texas Christian University campus in Fort Worth Texas (Hora and Miller, 1994; Mustard et al, 2003; Edwards, 2004; Manitoba, 2007; Birker et al, 2002). Tyndall Stone is quarried near Winnipeg Manitoba, the geographic centre of the North American continent so rail transport was and is critical for the distribution of Tyndall Stone.

Stone of appealing colour and sound physical character, in plentiful supply and accessible to sea or rail transport can make a nationally or internationally traded product. But a number of buildings of historical interest are made with stone that demonstrates that all stone has value and no stone should be wasted. In Montreal Maison Peter Lyall (1889) is built from Scottish 'Old Red Sandstone.' This brownstone was used as ballast to stabilize empty ships coming to Canada during the fur trade in the 18th and 19th centuries and after being unloaded to make way for fur was used as a building stone (Birker et al, 2002). In Vancouver Gertrude Lawson House (1939) is made with granitic and volcanic fieldstone brought to Vancouver from New Zealand as ship ballast (Mustard et al, 2003) and the Race Rocks Lighthouse (1860) near Victoria is made with Scottish granite that came around Cape Horn (Hora and Miller, 1994). Glacial boulders (fieldstone) are a ready supply of stone in Canada. They form a multicoloured display in Saskatoon's first permanent school house (the Little Stone Schoolhouse (1887) (Mysyk and Kulyk, 2006). Cabot Tower (1897-1900) was built to mark the 400th anniversary of John Cabot's discovery of Newfoundland and is the place where Guglielmo Marconi received the first transatlantic wireless signal in 1901. The Tower is made with local and Nova Scotia sandstone stone salvaged from stone barracks built on the site in 1842-1843 that were destroyed in the Great Fire of 1892 at St. John's (Newfoundland and Labrador, 2007).

The turn of the 19th century saw building stone used in many public and commercial buildings but was the start of a decline in the use of stone and an explosion in the use of gravel for concrete. The Portland cement industry was introduced into Canada in 1890s and concrete began to displace stone as a material for building foundations and engineering structures (Ontario, 2007). Rogers House (1901) has the earliest concrete basement in Vancouver (Mustard et al, 2003).

Gravel has been used for centuries but huge consumption came with the expansion and improvement of the road and rail infrastructure and the widespread use of sand and gravel in concrete. Gravel deposits, particularly deposits of glaciofluvial origin, are widely distributed across Canada and provide a ready source of material for concrete (Edwards, 1989). In 1886 national stone production excluding stone for cement and lime was about 33 times the recorded sand and gravel production of 125, 865 tons worth $24,226 ($CD). In 1900 national stone production was about 16 times the value of sand and gravel and by 1925 that ratio had dropped to 2 to 1. Sand and gravel production in 1930 exceeded 28 million tons and $8 million ($CD), roughly a one hundred fold increase from the turn of the century. During the depression sand and gravel production (1933) plummeted to only half the amount produced just three years before but that amount was now more than 12 times the national stone production (Natural Resources Canada, 2007a).

The latter half of the 20th century saw total Canadian aggregate production increase from about 82 million tons in 1950 to about 393 million in 2000. In 1950 about 88% of the aggregate production was sand and gravel and the relative values were $0.50 ($CD) per ton for sand and gravel and $2.66 ($CD) per ton for crushed stone. Essentially crushed stone and gravel are substitutes in the market so if the distance to market (cost of haul) and supply is similar, production favours gravel. In 2000 about 67% of the aggregate production was gravel and the relative values were $3.70 ($CD) per ton for sand and gravel and $6.78 ($CD) per ton for stone (Natural Resources Canada, 2007a, b). Stone steadily increased its share of the aggregate market over the fifty year period presumably as the closer and easier to mine gravel deposits were depleted.

In 2004 mineral aggregate was one of the top five mineral commodities produced in Canada. This production included about 246 million tons of sand and gravel worth $1.168 billion ($CD) and about 123 million tons of crushed stone worth $872 million ($CD) (Natural Resources Canada, 2007b). Four of the five largest aggregate operations in Canada occur along the Straits of Georgia, the Strait of Canso and the Great Lakes where large volumes of quality material can be transported cheaply. Gravel from Sechelt and crushed limestone from Texada Island are loaded on bulk carriers and shipped to markets from Alaska to California (Panagapko, 2005a). A quarry at Cape Porcupine on the Nova Scotia mainland side of the Strait of Canso ships about four million tons of high quality crushed igneous stone along the eastern seaboard (Fensome and Williams, 2001) and a limestone quarry on Manitoulin Island in Ontario has ready access to the Great Lakes. The fourth largest quarry occurs at Dundas on the Niagara Escarpment, right in the middle of Canada's largest market, the greater Toronto region (Panagapko, 2005b).

During the 20th century first steel then reinforced concrete began to replace massive stone for the structural framework of buildings until only a thin curtain wall of dimension stone or brick was required. The development of Vancouver's current central business district in the early 20th century is reflected in the evolution of building architecture and stone choices. New techniques in steel construction and concrete permitted the building of the first 'skyscrapers' as opposed to the generally lower, broader buildings built of sandstone in the Gastown area (Mustard et al, 2003). However, the aesthetic appeal and the lasting finish provided by stone and the availability of a huge variety of international stone has resulted in a resurgence in the use of stone as exterior cladding and interior finishing in many modern buildings in larger Canadian cities (Hora and Miller, 1994). Many provinces, including Alberta, have reported an increased interest in re-establishing old quarries or developing new ones.

In 2004 Canada produced about 719 thousand tons of building stone of all types including dimension and monumental stone, stone for walls and steps, tile, flagstone and landscaping rock. This production was worth about $87.1 million ($CD) and came from about 187 quarries: 77 quarries in Quebec, 81 quarries in Ontario, 5 to 10 quarries each in British Columbia, Newfoundland/Labrador and Manitoba and 2 or 3 quarries in each of Nova Scotia, New Brunswick and Alberta (Panagapko, 2007). Of this production 41.6% was limestone and dolostone, 36.5% was granite including gneiss, 10.8% was sandstone, 7.9% was slate and shale and 3.0% was marble (Panagapko, 2005b).

Alberta

Alberta is one of the youngest provinces and has a condensed version of the Canadian building stone history described above that illustrates the same principles. On November 7, 1886 a devastating fire destroyed many of the wooden buildings on Calgary's main street. Calgarians were determined to rebuild but this time with a fireproof, more durable material: stone. Massive Paskapoo Sandstone outcrops along the Bow and Elbow Rivers that flow through the city provided the source of stone and stonemasons brought from Europe provided the skill. The Sandstone Era was born: by 1890 over 50% of Calgary's tradesmen worked in the sandstone industry and fifteen quarries operated in and around Calgary. Sandstone was used in most large government buildings (City Hall, 1911 and the Court House, 1914), schools (King Edward School, 1912), churches (Cathedral of the Holy Redeemer, 1904), and private buildings (Alberta Hotel, 1888 and Lougheed House, 1891). The beautiful golden-brown sandstone buildings gave the streets an aura of prosperity and substance that transformed a pioneer settlement to an urban centre and gave the city its deserved title, The Sandstone City (City of Calgary, 2006).

Following the opening of the first quarry in Calgary in 1886 the demand for Paskapoo sandstone mushroomed; stone was shipped to other Alberta cities and quarries were opened from Fort Macleod in the south to Entwistle, west of Edmonton, in the north (fig. 2). Edmonton has the most significant Paskapoo sandstone building, the Alberta Legislature Building. It is built mainly of rock quarried at Glenbow, just west of Calgary and shipped by rail to Edmonton (Mussieux and Nelson, 1998).

The Calgary fire of 1886 also sparked the brick industry. Brick was made from the shale that is interlayered with the Paskapoo sandstone. Calgarians began to build their chimneys out of fireproof brick and from 1907 to 1912 brick homes were in vogue. Edmonton is rich in mineral resources (coal, gold, brick clay, oil and gas) but those riches do not extend to local stone. The Humberstone Brick and Coal Company was the first (1881) of fifteen brick plants to operate in Edmonton. The North Saskatchewan River floodplain was the primary source of clay and valley bricks now a century old were used to construct some of the University of Alberta buildings. Many of Edmonton's oldest buildings combine locally produced red brick with Paskapoo Sandstone lintels and sills (Maclean Block, 1909 and the Metals Building, 1914). Between 1881 and 1913 the brick industry thrived across Alberta with more than 125 brick plants operating in total (Manson, 1982).

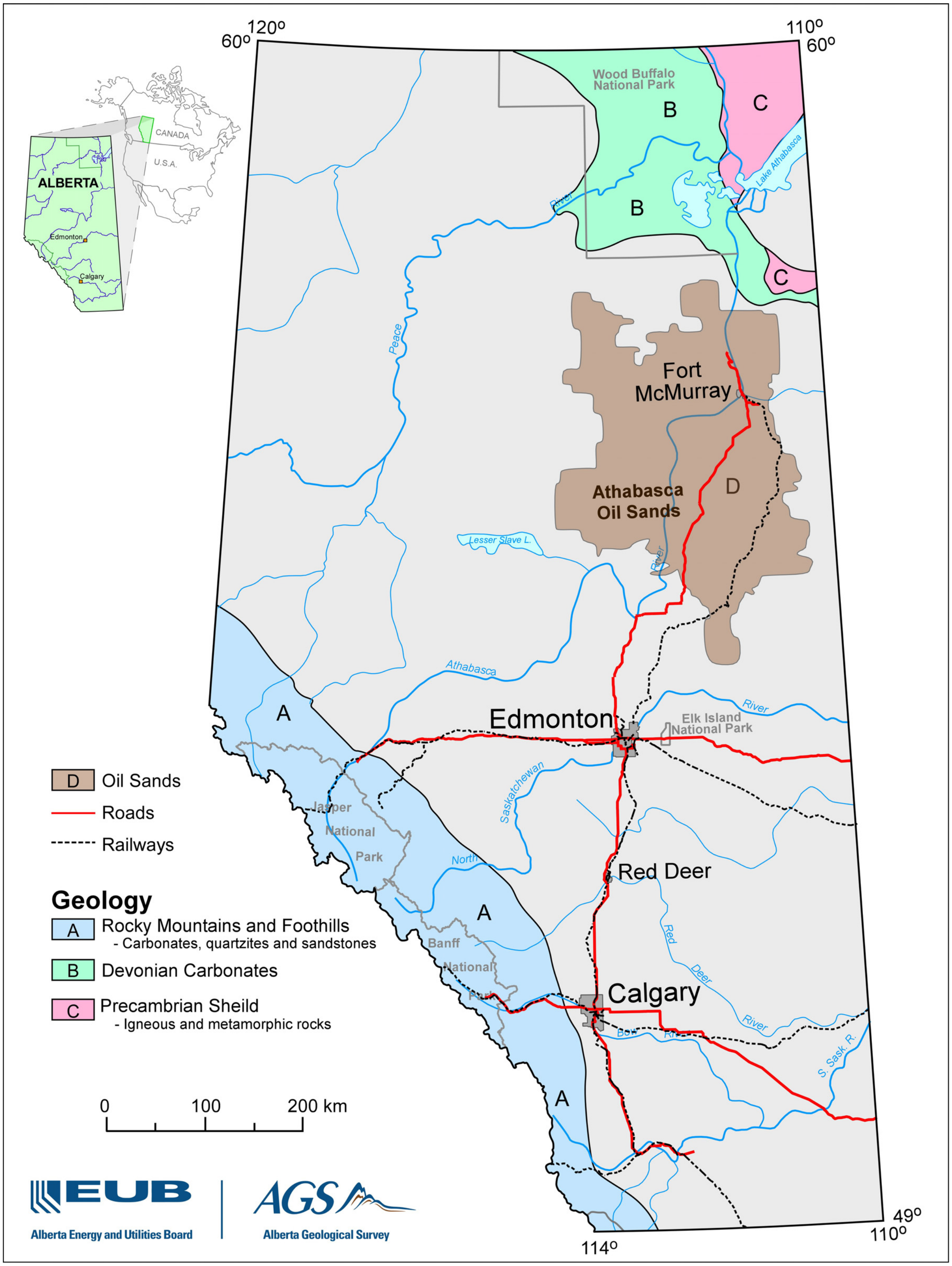

Figure 2. A map of Alberta showing the cities and regions with large aggregate demand, major transportation routes and geological regions with building or crushed stone potential.

Both the building stone and brick industries were hit hard by the depression of 1913 and the Sandstone Era came to a close in 1915 with the outbreak of the First World War when employees left to serve in the armed forces. There is some renewed interest in Paskapoo Sandstone for restorative work and decorative stone in new residential construction. The brick market was further reduced with the coming of structural steel and reinforced concrete and the depression years of the early 1930s spelled the end of an era for small brickyard operations (Manson, 1982).

The other Alberta stone is Rundlestone; flaggy, fine-grained, blue-grey sandstone (fig. 1). Rundlestone is seen in the walls of many picturesque buildings in Banff, notably the Banff Springs Hotel (1928) (Hamilton, 2006). Banff created an aesthetic image by requiring the use of Rundlestone. This ensured demand for quarries in the area, lent credibility and appeal to the stone and in turn provided opportunity for market expansion. Two small but very active quarries near Canmore are taking advantage of the appeal and the stone is now widely used in Alberta and is even exported as far away as Japan. The producers are also finding ways to add value to the Rundlestone resource: the rock contains fossils, sedimentary structures and tectonic features that make special pieces virtual pieces of art, it is hand sorted and palletized into very specific sizes for multiple uses, blocks are trimmed for use as building stone and former waste rock and fines are being sold as aggregate and packing material for pathways.

Most of Alberta's 'stone' history has been dominated by sand and gravel. Archival photos from 1905 show horse drawn teams hauling gravel from the river valley at Edmonton and by 1910 , the High Level Bridge, our the first major structure using concrete, was under construction (Edwards, 1993). Sand and gravel production in Alberta exploded from about 192 thousand tons in 1946 to about 31.5 million tons in 1970 due to massive road construction. Alberta has the fourth largest provincial population in Canada but is the second largest producer of sand and gravel.

A comparison between 1960 and 2004 of crushed stone as a percentage of total aggregate production for the major producing provinces (Ontario, Quebec, Alberta and British Columbia) shows a definite trend. The use of stone increased from 30% in 1960 to 56% in 2004 in Quebec, from 18% to 37% in Ontario and from 10% to 22% in British Columbia. From 1960 to 2004 Alberta had by far the largest increase in total aggregate production, about 350%, but has resisted the national trend: the use of stone remained essentially insignificant at 1% (Natural Resources Canada, 2007a).

Although Alberta gets almost all of its aggregate from surficial sources the assurance of sand and gravel supplies looks far from certain. In 1991 one third of Alberta municipalities surveyed predicted that gravel supplies would be depleted in their region in about 20 years and 3 of the 7 longest average haul distances belonged to regions with the largest populations and greatest demand for aggregate (Calgary, Edmonton and Red Deer) (Edwards, 1998a). In 1995 the president of the Alberta Sand and Gravel Association noted that sand and gravel was being consumed at twice the rate at which it was being found (Edwards, 1998b). An analysis of the gravel resources in the municipality south of Calgary, one of Calgary's major suppliers, predicts the depletion of the gravel resource in a few decades and huge transportation costs as the haul grows longer (Edwards and Budney, 2007). Factors are ripe for a major shift to crushed stone production and use in Alberta. The first dedicated crushed stone aggregate was quarried in 2006. Is this the start of a gradual change or an avalanche?

OBSERVATIONS AND LESSONS

Beware the Paradigm Shift

Historically the start and the end of Alberta's sandstone era came abruptly. Did Albertans in these industries anticipate this paradigm shift? Are we ready now to anticipate, perhaps even design for, some equally large shift? For about a century we have been in the 'gravel age'. Transportation of gravel in Alberta started with horse drawn wagons but for generations now has employed trucks. Gravel haul distance has gradually increased as the nearest deposits are consumed until the haul is as much as 75 miles in some regions. What if longer truck transport becomes untenable or unpalatable not only because of haul cost but also environmental and climate concerns? Is government and industry ready for a swing to crushed stone and rail transport? Could we contemplate dedicated rail to resources? It is apparent that the state needs to identify our current and future markets and their relative demands, then assess the transportation costs, routes and modes and finally map, inventory and protect aggregate resources.

Identify the 'fortresses and canals'

Massive projects such as fortresses and canals consumed huge amounts of building stone and spawned quarry and skills development that continued beyond the original project. What are the megaprojects of today and tomorrow in Alberta? First and foremost are the oil sands projects in the Ft. McMurray region (fig. 2); the construction and operation of which can require millions of tons of aggregate (Hudson, 1981). Coupled to oil sands mining is the urgent requirement for upgrading of the highway and the rail service between Edmonton and Ft. McMurray (fig. 2). Almost certainly the demand for rail construction, road improvement and probable pipeline construction along the narrow Edmonton to Ft. McMurray corridor constitutes another project of massive proportions. Historically the railway meant greater access to stone for architects and builders in faraway places like Edmonton. Perhaps improved and even new rail service in northeast Alberta will provide access to stone resources for use beyond this region. Other obvious markets in Alberta are Edmonton and Calgary (fig. 2) but there is very large, widely disseminated and largely unknown demand for roads and installations from the conventional oil and gas and the forestry industries in northern Alberta. Mapping, inventory and protection of aggregate resources in the key demand regions should begin as soon as possible.

What made Alberta rock?

Building stone use was encouraged by local leaders and sometimes enforced by civic governments to prevent the spread of fire that endangered lives, business and trade. The use of local stone was also a deliberate and successful way to infuse a sense of pride, community and confidence in booming Alberta towns and cities. That choice is still felt as an increased demand for rock in the restoration of these now historic buildings. Banff created an aesthetic image by requiring the use of Rundlestone and provided a base for the local industry. Are we building Alberta's future heritage now, proactively 'developing' our history? Edmonton and especially the new boom centres like Ft. McMurray appear to be simply overwhelmed by the need for new development. Is it still appropriate; is it time, to take pride in Alberta rock? Would provincial regulations favourable for Alberta stone development and use be useful, possible?

Let’s use that ‘stinking stone’

What kind of stone industry can thrive in Alberta? Realistically we need to use the ‘stinking stone’ available. Quebec City stinking stone and Calgary Paskapoo Sandstone had something in common; they were readily exploitable, very low cost because they didn’t require transportation and adequate for the job at hand. We need to recognize Alberta stone for its value, not devalue it for what it is not. Rundlestone producers are attempting to maximize the value of their resource. This intelligent use of the rock should remind us when mapping or evaluating stone to add a touch of imagination to our science. Some buildings are declared heritage sites because they involve the unique use of rocks in limited supply: a few houses in Vancouver, Montreal and the Maritimes are remarkable because they were made from ship’s ballast. We need to use this kind of enterprise when evaluating Alberta resources: assume every rock has a use (the highest value is best of course) and plan to use everything, including the hole. All holes don’t have to produce a Butchart or Royal Ontario gardens but routine practical reclamation and occasional examples of brilliant after-use add saleability and acceptability to specific development proposals and a favourable climate for surface mining in general.

SUMMARY AND RECOMMENDATIONS

The history of Canadian stone use and buildings is interesting in its own right and valuable for educating the public in the role and use of building stone and other stone resources. This history also contains information on principles and insights into paradigm shifts that are helpful in designing stone resource evaluation and mapping plans for Alberta. In summary it translates into the following recommendations. We should continue to update our surficial (gravel) resource information but focus on the evaluation of the near-surface bedrock (stone) formations for a spectrum of potential resource uses. These studies should begin closest to the areas of current demand and along the transportation routes to these areas, and then proceed to areas identified by a comprehensive market and demand analysis (fig. 2). The study should dedicate itself to areas where development is feasible and if potential is established these areas should be tagged and monitored for resource use.

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Industrial Minerals: Almost a Generation of Change

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ABSTRACT

Back when the Forum assembled in Colorado in 1979, Iranian militants seized the hostages the US embassy in Teheran and Margaret Thatcher became the new prime minister in Great Britain. Over the intervening years, the industrial minerals industry has grown in size, stature, and sophistication and yet remains largely unknown to many. To be sure, communications on industrial minerals have improved immeasurably, and political change has demystified markets behind the Iron and Bamboo curtains. However, the supply side of the industry has been rationalized, and in many cases hijacked by a few corporations and still fewer countries. Demand is shifting from the traditional moribund centers in the West to the expanding markets of the East. The constant buzz is around the "China effect" as that country has evolved from a minor net importer to a dominating net mineral exporter, and in some cases is currently in the process of reverting to an importer to support its rampant manufacturing growth. At the same time, other large mineral consumers like the United States and Europe have become increasingly reliant on imports, boosting world trade activity in even the most basic industrial mineral. In all this metamorphosis, certain minerals have emerged as winners and others as losers in a highly competitive field where consumers expect more for less. Markets have peaked and fallen, some to be replaced by uses unheard of almost a generation ago and requiring new grades with adjectives like calcined-, delaminated-, or nano-. This paper will address some of these issues and trends using specific mineral and company examples.

The more things change, the more they stay the same

Back when the Forum assembled in Colorado in 1979, the Shah of Iran was replaced by Ayatollah Khomeini and Iranian militants seized US hostages and held then for 444 days. In 2007, British sailors and marines were seized and held for more than 10 days. It was the year of the overheated reactor at the Three Mile Island nuclear facility in Pennsylvania which threatened to melt down and the Soviet invasion of Afghanistan stirred protests worldwide. Today, there is talk of the revival of nuclear power and military action in Afghanistan remains in the headlines. Margaret Thatcher became the new prime minister in Great Britain – she would last eleven years before being ousted; by the end of 2007 Tony Blair will have suffered the same fate. As the French say, *plus ca change, plus c'est la meme chose*. In other news, John Wayne and Nelson Rockefeller died and an American and Brit won the Nobel Prize for developing the now common CAT scan. The Sugar Hill Gang released the first commercial rap hit, "Rapper's Delight" and the Album of the Year was Saturday Night Fever. Apocalypse Now was playing in cinemas. In sports, Pittsburgh defeated Dallas in the Super Bowl and Pittsburgh defeated Baltimore in the World Series.

This was the beginning of what could be termed as the *Industrial Minerals* age.

In the first editorial, the first editor of *Industrial Minerals*, Pete Rowbotham, defined what would be included in the new journal and set out the fledgling magazine's editorial policy as a nonmetallic extension of *Metal Bulletin* explaining that "The impression that has been fostered in the past by, amongst other things, the absence of a central trade paper for the industry, is a rag bag of unimportant commodities. While not quite the equal of the fuels or metallic minerals either in volume or value of production, the industrial minerals deserve far greater attention as a group than hitherto." Progress to this end has been made in the intervening thirty-some years, although in many respects industrial minerals remain the "third world" of the extractive industries behind the newsworthiness of energy and the perceived glamour of the metallics.

COMMUNICATIONS

Prior to the launch of *Industrial Minerals*, information on industrial minerals was limited to AIME/SME's *Industrial Minerals and Rocks* first published in 1937 updated periodically so that the 7th edition has been published this year (2006). Information from various government sources including the US Bureau of Mines and the British Geological Survey helped shape and color statistics. Based on his classes at Ohio State University, Robert L. Bates emerged as the industry's *de facto* guru through publications like *Geology of Industrial Rocks and Minerals* (1960) and *Geology of the Nonmetallics* (1984) and *Industrial Minerals - Geology and World Deposits* (1990) co-authored with Peter Harben. In 1965, he founded the now annual Forum on the Geology of Industrial Minerals (this is the 43nd meeting) and talked passionately about the subject including "Channels of communications in the industrial minerals field" as the closing paper at the very first *Industrial Minerals* Conference in London in 1974.

Since that time, numerous publications and events have helped spread the word – periodicals like *Mineral PriceWatch*, *Asian Glass*, *Asian Ceramics*, textbooks like *Industrial Minerals HandyBook* and *Industrial Minerals A Global Geology*, multi-client reports by Roskill, Fertecon, CRU, and Kline, and the surviving government sources such as the US Geological Survey. Conferences have become specialized and far flung offering detailed treatments in exotic locations.

The internet has become an integral part of communications. Information that took weeks by snail mail can now be downloaded in the time it takes to say "broadband". Company profiles and specification sheets are available with the click of the mouse, and articles can be carried as PDFs on a laptop or Palm Pilot. The internet allows small mineral producers in China and India to advertise wares internationally 24/7. However, despite the advances in technology, there are severe limitations. Information on the web may be unfiltered and misleading promotional pieces designed to boost share prices rather than inform, and there is rarely any intelligent analysis of the data. Many have tried and failed to buy and sell industrial minerals on the net using reverse auctions and the like – in the end the complexity of the industrial minerals business caused the programs to crash and burn.

LOSS OF GOVERNMENT INTERFERENCE

In the past, most governments staffed a department charged with collecting and disseminating information on their country's mineral industry. The highest profile was in the United States where on May 16, 1910, Congress established the US Bureau of Mines (BOM), a government entity that "conducts research and collects information concerning almost every activity involved in recovering minerals from the earth, making them into useful products, and materials for future use." For 85 years, the BOM's free publications on mineral commodities were distributed to more than 50,000 subscribers worldwide. Publications like *Mineral Facts and Problems,* last published in 1985, remains a classic which is often imitated but never bettered. Then on September 30, 1996 the BOM was unceremoniously killed off in order to save its $132 million budget and the disorientated and dispirited remnants folded into the US Geological Survey (USGS). This was a step in the process to reduce mining and more recently geology from the USGS as the biological division has developed into the majority stakeholder of the organization. Most equivalent organizations suffered a similar fate at the hands of governments of all stripes – the British Geological Survey, Natural Resources Canada, and the Council for Geoscience in South Africa – which are a shadow of their former selves with slashed budgets and minimal staffing. It is ironic that in the so-called information age, the level of communications has deteriorated and the availability of detailed information diminished. More and more, government statistics contain the dreaded "W" (withheld to avoid disclosing company data) due to rationalization reducing the number of producers to less than three and the lack of manpower to press for information.

CHANGES IN SUPPLY

Industrial commodities to modern marvels

In the early issues of publications like *Industrial Minerals*, the major emphasis was on commodity minerals used in heavy industry, for example, sulfur for chemicals, asbestos for construction and friction products, fluorspar for steelmaking, barite for oil drilling, and potash and phosphate for fertilizers. This was sprinkled with a few exotic products like borates and celestite used on a smaller scale, but as the industry evolved so it included still more exotic varieties like rare earths, zeolites, and wollastonite. Mined products had to compete increasingly against synthetic products such as seawater magnesia or synthetic zeolites or byproduct minerals like recovered sulfur, flue gas desulfurization (FGD) gypsum, and byproduct sodium sulfate. Increasingly strict environmental laws encouraged or mandated recycling affected the markets for several glass raw materials and eventually even construction materials. Competition encouraged many mineral producers to employ more elaborate processing techniques to produce value-added grades such as calcined or the more recent nano-particle size. Ever faster and more automated methods of manufacture demanded raw materials with a high degree of uniformity that in turn placed heavy responsibilities on the suppliers of raw materials. Certain specifications were met by blending minerals from various sources, for example graphite houses may blend grades from China, Brazil, and Canada to satisfy the needs of a consumer and large paper plants worked with a kaolin producer to develop a specification required to produce a special paper type.

Major supply changes

Some examples of major changes in the supply of minerals are outlined below.

Asbestos

In the early 1960s a correlation between excess exposure to asbestos fibers and respiratory cancer diseases was firmly established, putting the industrial mineral industry squarely in the spotlight. Chrysotile was vilified and several “related” minerals such as talc, erionite (zeolite), and wollastonite were dragged into the debate over the health risks as medical researchers and lawyers salivated over the prospects of multiple class-action suits. The presence of asbestos in some mineral deposits extended the concerns; for example W.R. Grace’s vermiculite deposit in Libby, Montana, was closed and the company remains in the lawyer’s crosshairs. There has been a strong movement toward stricter regulations, with a ban implemented for the most part in developed countries where substitute materials or alternative products are readily available and it is economically feasible to use asbestos substitutes. In lesser-developed countries where economics and the level of industrial development is a factor, asbestos substitutes are not yet considered to be a suitable option in many cases. Countries that have banned (either a complete bans or a ban with exemptions) or are phasing out the use of asbestos and in some cases, asbestos products, include Argentina, Austria, Belgium, Chile, Denmark, Finland, France, German, Italy, Netherlands, Norway, Poland, Saudi Arabia, Sweden, Switzerland, and the United Kingdom. Despite the continued opposition to the use of asbestos, the USGS expects that markets for asbestos probably will persist, albeit at lower levels as substitutes and alternative products gain favor in the remaining world markets. However, this process will likely occur over several decades and certain specialized applications will survive, particularly for matrix-based products, since this is a unique natural product.

Lithium

Hard-rock mining of pegmatitic minerals has been the traditional source of lithium, in particular open-pit mines in North Carolina in the United States, Bikita in Zimbabwe, Manitoba, Canada, and in Western Australia. However, in the mid-1990s the North Carolina spodumene mines were abandoned in favor of extraction from the salars of South America. This started in 1986 when Cyprus Foote Mineral closed its spodumene mine to concentrate its efforts on brines of the Salar de Atacama, a dry salt pan some 280 km inland from Antofagasta, northern Chile, together with its existing brine operation at Silver Peak, Nevada. FMC Corp.'s Lithium Division followed suit with the announced closure of its North Carolina spodumene operation and the parallel startup of its Salar del Hombre Muerto brine operation in Argentina supplemented by purchases from Chile. The final nail was put in the spodumene coffin in 1996 when SQM started up its 18,000 tonnes/year lithium carbonate plant based on “waste” brines from the Salar de Atacama (the production costs were covered by potash production). Low production costs allowed the brine-based lithium carbonate producers to dominate the market and price reductions rendered hard-rock mining uneconomic except for some specialized glass and ceramic applications.

Soda ash

Large-scale commercial exploitation of natural sodium carbonate (soda ash) began in 1916 at Lake Magadi, Kenya, followed in 1927 by production at Searles Lake, California. Then in 1938 trona was discovered in the Green River basin of Wyoming, and in 1953 FMC Corporation commenced production with a 300,000 tonnes/year plant. Since that time, production of soda ash in the United States has expanded to 13.5 million tonnes derived from four producers in Wyoming plus 1.45 million from Searles Lake and 1 million tonnes from Colorado based on nahcolite (opened in 2000 and struggling to survive). The availability of low-priced natural soda ash from the western United States has had a profound affect on domestic and world markets.

Initially, it eliminated all the synthetic (Solvay) plants in the United States, with the last one in Syracuse, NY closing in 1986. The formation of the American Natural Soda Ash Company or ANSAC in 1982 and the use of dedicated unit trains allowed US soda ash producers to compete with traditional synthetic soda ash in most parts of the world. Increased access to US exports encouraged capacity expansion and investment in Green River by foreign companies such as Sumitomo Corp., Nippon Sheet Glass Co., Asahi Glass Co., and Tosoh of Japan, Oriental Chemical Industries Chemical Corp. of Korea, and Solvay et Cie of Belgium. Ownerships changes have been common and recently have extended beyond Wyoming with Solvay America, Inc. taking over the Colorado operation in 2003 and Sun Capital Partners, Inc. (Searles Valley Minerals, Inc.) taking over the California operation in 2004.

Soda ash represents one of those commodities where China has evolved from net importer to exporter. After more than a century of US leadership, in 2003 China overtook the United States as the world largest producer of soda ash. During the 1980s the United States was exporting more than 1 million tonnes/year of soda ash to China, and then in the early 1990s this gradually declined to zero after which Chinese exports competed with ANSAC exports in certain parts of the world market. After a generation of change, three dominant groups – Solvay, ANSAC, and China – now dominate the world soda ash market.

Kaolin

Traditionally, paper-grade or refined kaolin production was restricted to operations in Georgia in the United States and Cornwall in the UK. Then in the 1970s, there were some articles on the potential of product from Brazil and Australia, and eventually large-scale operations started up in the eastern Amazon region of Para and Amapá states in Brazil (production in Australia began but closed in 1996; there are renewed efforts to start production in Queensland). Today, about half of the approximately 13 million tonnes/year of refined kaolin produced in the United States, the UK, and Brazil enters deep-sea trade, and some exports from Brazil are finding their way into the paper markets of the northeastern and mid-western United States.

Partly encouraged by competition from carbonates as a paper filler and even coating agent, the range of grades of kaolin available has increased. Intensive wet processing generates the exactly fractionated range of particle sizes necessary for various paper-coating products, and traditionally ultra-magnetic and chemical methods have been used to improve brightness and whiteness. More recently, pigment-grade kaolins have been made by calcining at temperatures up to 1,050°C in order to change the atomic structure and improve both pigment brightness and opacity (although at the cost of increased viscosity and abrasivity). Calcined kaolins compete with much higher-priced pigment minerals such as titania.

Carbonate

Over the past thirty years the consumption rate of mineral pigments and fillers has increased in parallel with the escalating demand for paper, paint, plastic, rubber, adhesives, and sealants. At the same time, demand has increased with the increase in the loading factor due to improved techniques. Estimates are that the worldwide demand for mineral fillers in paper and board is approximately 20 million tonnes of which 45 percent is kaolin, 25 - 30 percent GCC, 10 - 12 percent PCC, and 15 percent others including talc. However, this general worldwide number clouds differences in the consumption pattern by region. The lack of kaolin and abundance of carbonates in Europe encouraged the switchover from acid to alkaline papermaking processes in Europe in the 1980s, whereas the availability of kaolin from Georgia and latterly Brazil in North America delayed the change until the 1990s when the use of both ground calcium carbonate (GCC) and especially precipitated calcium carbonate (PCC) increased. One of the phenomenal developments over the past 30 years was the development of on-site production plants where PCC facilities are maintained adjacent to the paper mill and grades are custom engineered for the paper company. The first PCC satellite plant was opened in 1986 at Consolidated Paper Inc.'s Wisconsin Rapids paper mill in the United States. This concept was pioneered by Pfizer Inc., the predecessor of the current leader, Specialty Minerals Inc., a wholly owned subsidiary of Minerals Technologies Inc. The company has over 50 satellite plants in 14 countries around the world and account for about two-thirds of world PCC capacity with the balance derived from merchant plants where PCC is manufactured for sale to a variety of industries. The local availability of PCC, especially in North America where kaolin is plentiful and GCC scarce and mainly based on marble, was instrumental revolutionizing papermaking technology.

Magnesia

Traditionally, magnesia for chemicals and refractories was derived from the minerals magnesite or dolomite. However, interruptions in supplies during World War II encouraged the development of process to extract magnesia from seawater. A plant in Hartlepool, UK, was built in less than twelve months by the Steetley Company on behalf of the Ministry of Aircraft Production. The Harrington Shore plant was geared up to produce 40,000 tonnes per annum and was the pioneer that allowed magnesia production to be largely independent of geology thus allowing large-scale output in the United States, Japan, Korea, Italy, and Ireland. Some have closed, including Hartlepool in 2002, in the face of competition from cheap magnesia from China, North Korea, and Russia, other brine sources such as the Dead Sea in Israel/Jordan and Laguna del Rey, Mexico, and a declining market. Many of the original names like Steetley have gone, and the emphasis is in high-quality grades servicing the refractories industry.

Sodium sulfate

This is a mineral commodity buffeted over the years by involuntary production and disappearing markets. Traditional production was centered on Canada and Russia (from the mineral mirabilite) and various parts of South America, Mexico, western United States, Spain, and India (from thenardite). However, large quantities were produced as a byproduct of numerous manufacturing processes including nitrate/iodine processing (the Guggenheim counter-current leaching of caliche ore in Chile); rayon spinning, the Mannheim process for the manufacture of hydrochloric acid; and the manufacture of sodium dichromate; phenol, resorcinol, and cresylic acids (phenol cake); formic acid; boric acid; lithium carbonate; and ascorbic acid (vitamin C). At the end of the 1980s, world production of sodium sulfate was split evenly between synthetic and natural, but since then the natural has increased to account for over 70 percent, mainly due to increased Chinese output. Natural production elsewhere has fallen as prices suffer by a lack of control on the production end and reduced demand in major end uses such as detergents.

Sulfur

Many commercial sources of sulfur based on the traditional native sulfur or pyrite roasting have been eliminated by the availability of involuntary sulfur produced as a byproduct of efforts to meet environmental requirements that limit atmospheric emissions of sulfur dioxide. In the United States, Freeport-McMoRan Sulphur Inc. closed the last domestic Frasch mine, Main Pass, in 2000 and Poland is the only country producing more than 500,000 tonnes/year of native sulfur by using either the Frasch or conventional mining methods. Recently, production of recovered elemental sulfur, which is a nondiscretionary byproduct from petroleum-refining, natural-gas-processing, and coking plants, and byproduct sulfuric acid production at copper, lead, molybdenum, and zinc roasters has outpaced sulfur demand resulting in increased stocks and depressed prices.

Salt

Over the past generation, annual worldwide salt production has increased by more than 40 percent from less than 150 million tonnes in 1970 to almost 215 million tonnes in 2004. Over the past decade changes to the supply have included a 30+ percent increase in output from China plus smaller but significant increases from the United States, Canada, Mexico, Chile, India, and Germany. Trade patterns have remained stable with some 30 million tonnes/year of salt entering deep-sea trade, equivalent to about 15 percent of production. Of this trade, the top 5 exporters -- Australia, Mexico, Canada, the Netherlands, and Germany -- account for more almost 80 percent of the total; the top 5 importers -- Japan, the United States, South Korea, Belgium, and Germany -- account for almost 70 percent of total imports. The industry is now highly influenced by salt superpowers like Mexico and Australia serving distant markets through efficient and large-scale transportation. A single operation at Guerrero Negro in Baja California Sur, Mexico, operated by Exportadora de Sal SA (ESSA), owned by the Mexican Government (51 percent) and Mitsubishi Corporation of Japan (49 percent), produces some 7 million tonnes/year of salt servicing markets in North America and Asia. Large-scale salt production in Australia is mainly from solar salt operations in Western Australia where a combination of a hot dry climate, good port and infrastructure, and proximity to markets in Japan and other consumers in Southeast Asia has encouraged development. Salt production in Western Australia has increased from less than 5 million tonnes in 1985 to current levels of more than 10 million tonnes and Dampier Salt Ltd. is Australia's largest salt producer and the world's second largest salt exporter.

Beryllium

Traditionally, much of the world's beryllium came from beryl mined in Brazil, Russia, Madagascar, China, and Kazakhstan. However, much of this has disappeared with the start of Brush Wellman Inc.'s production of bertrandite in Utah which now contributes about 85 percent of the world total.

Phosphate rock

In the 1970s, the United States was the leading producer and consumer of phosphate rock and was self sufficient. At the time, most of the international trade was in the form of rock concentrates which were upgraded and converted to fertilizers close to the point of consumption. Morocco emerged as the world's largest exporter, servicing much of Europe and parts of Asia. A concerted effort by Office Chérifien des Phosphates (OCP Group) to switch to more concentrated and value-added forms such triple superphosphate and phosphoric acid changed the pattern of trade and put many companies in Europe out of business. Trade continues to increase, largely due to higher exports from Egypt, Jordan, and Morocco and increased imports into Central Europe, Eastern Europe, India, and the United States. In contrast to 1970, the United States is the leading importer of phosphate rock in the world with about 2.5 million tonnes/year, almost exclusively from Morocco. The Government of China imposed limits on exports of phosphate rock to maintain an adequate supply for domestic fertilizer production. Combined diammonium phosphate (DAP) and monoammonium phosphate (MAP) production grew by 25 percent in 2004 as Chinese manufacturers reduced their output of low-analysis fertilizers in favor of ammonium phosphates and NPK fertilizers. China’s DAP exports grew also, with companies in the southern provinces selling DAP to the Philippines, Thailand, and Vietnam.

Gypsum

Increasingly, environmental considerations have influenced the supply of minerals. Prime examples include sulfur and sulfuric acid, sodium sulfate, and salt (already mentioned). Another notable example is gypsum precipitated from a FGD plant attached to a coal-burning power plant or the neutralization of acid in a titanium dioxide pigment plant. Some gypsum wallboard plants are supplied by waste or by-product gypsum rather than the traditional mined material.

Strontium minerals

Early reports on celestite talked about the use in pyrotechnics and the potential for use in CRT color television glass. This potential was subsequently fulfilled and is currently being eroded by LCDs, plasma screen TVs, and the like. The last hurrah may be CRT TVs produced to allow the citizens watch the 2008 Olympics in Beijing.

UNFULFILLED POTENTIAL

Over the years several minerals have been touted for their potential which for the most part has remained unfulfilled. The most obvious example is natural zeolites touted for its application ranging from chicken feed to nuclear waste disposal. Fred Mumpton of SUNY Brockport, who died in 2004, wrote an article in *Industrial Minerals* in 1973 on the potential uses. This could be reprinted today with the same hope of optimism. Large corporations like Anaconda and Phelps-Dodge failed where small niche companies have succeeded after a long struggle. A great deal of data has evolved and there are a series of meetings, the next being Zeolite '06 is hosted by New Mexico Institute of Mining and Technology in Socorro, New Mexico, USA during July 2006. Garnet as an air-blast abrasive was touted as the natural and safe replacement of silica sand, slag, etc. However, growth in the market has been stymied by its relatively high cost and the fact that recycling is possible in theory but is difficult in practice under the normal circumstances. Wollastonite has unique and compelling chemical and physical properties, but the market has remained small and specialized. It could be called a niche market controlled by a limited number of suppliers servicing a limited number of consumers.

CHANGES IN THE MARKET

Over a period of more than 25 years, major mineral markets shrink and even disappear, to be replaced by new and expanding uses. The field of industrial minerals is a classic market economy with the substitution of one mineral by another based on technical superiority or more improved economics (that is a lower delivered price).

Substitution has always been an important aspect of the industrial minerals scene and continues to be critical for success. For example, in the paper industry calcium carbonate is a major challenger to kaolin as a filler and coater, and precipitated calcium carbonate competes with ground calcium carbonate in many applications. In certain parts of the world, most notably in Scandinavia, talc is a potential substitute for both carbonate and kaolin. In some cases, the same mineral is used, just less of it, due to increased efficiencies such as increased recycling and conservation.

Since mineral resources are distributed unevenly throughout the world, deep-sea trade in industrial minerals continues to grow. More highly developed techniques of materials handling and transportation have been a contributing factor, as has the demand by consumers for materials with special or unique properties irrespective of where these materials are found. Wyoming bentonite is delivered to oilrigs in the Persian Gulf region and caustic soda from the US Gulf region is exported to alumina plants in Australia. Soda ash from the western United States and potash from western Canada is transported via dedicated unit trains, port facilities, and ships to glass plants and farms as far away as Saudi Arabia and China. Low production costs and/or exceptional quality can overcome distance from market and compete successfully with more local products.

The center of the demand for many industrial minerals has shifted from the traditional manufacturing markets of North America, Western Europe, and Japan to China and fellow emerging nations in Asia as well as South America. Africa and the Middle East are growing along with the population, albeit from a small base. Of course, for years now China has dominated the headlines in the minerals world from everything from talc to tungsten with its metamorphosis from rural backwater through mineral importer to mineral exporter to mineral consumer to downstream exporter and possibly mineral importer.

China's escalating production rates and aggressive marketing has reshaped many markets such as magnesia, barite, graphite, soda ash, and fluorspar. Non-Chinese producers have closed as low-priced commodities from China flooded the market. Depressed prices discouraged the development of other producers, completing China's dominance in many areas. More recently, there has been a gradual shift whereby a combination of government control and escalating domestic demand in China has reduced the volume of exports, thus opening the way for new production units outside China. This is a gradual maturing of China in many ways.

Environmental and health and safety issues have become increasingly important in industrial minerals over the years. These issues range from simple mineral dusting problems at ports through the need to label mineral content and use specialized containers to the alleged health hazards associated with certain minerals and mineral-related products. At the very least they can represent additional handling or transportation costs, create barriers to sales and impinge on the prospects for future growth, and may even pose a long-term threat to the financial stability of the producing company due to the potential for litigation. Several minerals have been singled out for scrutiny – in particular silica, asbestos, fluorspar, and bromine. Crystalline silica is classified as a Class 1, Known Carcinogen by the International Agency for Research on

Cancer (IARC), a unit of the World Health Organization, and any mineral containing more than 0.1 percent crystalline silica must be so labeled. Asbestosis, claimed to be the cause of chronic lung disease, triggered the severe restrictions on the use of chrysotile asbestos in many countries and outright bans in others like France and Belgium which have crippled the asbestos market and encouraged substitution. At the same time, the use of beryllium products is said to cause beryllosis, a serious chronic lung disease. In a similar fashion the demand for fluorspar and bromine has been adversely affected by the Montreal and Kyoto protocols which aim to limit the use of products blamed for the apparent depletion of the ozone layer such as chlorofluorocarbons (CFCs), hydrofluorocarbons (HFC's), perfluorocarbons, sulfur hexafluoride, and methyl bromide. Several other minerals have health and safety concerns: the acicular nature of wollastonite and attapulgite crystals, the asbestiform mineral content in talc, the heavy metal content of barite used in drilling, the eutrophication of lakes through phosphates, the toxicity and carcinogenicity of hexavalent chromium, and the radioactivity associated with monazite and certain byproduct gypsum products.

The use of industrial minerals is expanding into many new areas. Over the past decade the market for pet litter, for example, has experienced phenomenal growth giving an enormous boost to the demand for attapulgite, sepiolite, bentonite, diatomite, zeolites, and even gypsum. A potential new producer should be aware of new developments and remain vigilant in seeking new concepts and markets. This is an ongoing process as the markets change. As the demand fro metallurgical-grade fluorspar (metspar) has contracted in many parts of the world, so the use of acid-grade fluorspar (acidspar) for fluorine-based chemicals and fluorocarbons has increased. In refractories, improved efficiencies and change from silica to alumina to magnesia has taken place. Regional bans on the use of phosphates in detergents encouraged the use of synthetic zeolites that in turn aided sodium silicate producers and therefore silica sand and chloralkali suppliers.

Name Calling

The mineral industry has changed greatly through rationalization. Gone are some of its biggest pioneers – Laporte ("Foremost in Fluorspar"), Murphyores (mineral sands in Australia), Steetley (the leading producer of magnesia in the UK), and English China Clays (synonymous with white fillers). Some have fallen by the wayside, but like so many "mom and pop" operations of early days, many have been absorbed into a handful of multinationals. Today, corporate behemoths dominate the industrial minerals industry – Unimin is the sole producer of nepheline syenite and a dominant force in silica and other minerals utilized in glass and ceramics, whereas Imerys of France has emerged as the world's major supplier of white filler minerals such as kaolin and calcium carbonate used in paper, plastics, paints, and the like. Talc de Luzenac (part of Rio Tinto) dominates in talc, Plüss Stauffer of Switzerland in ground calcium carbonate, Specialty Minerals Inc. of the USA in precipitated calcium carbonate, WGI Heavy Minerals, Inc. (formerly Western Garnet) of the USA in garnet, DeBeers of South Africa in diamonds, SQM of Chile in lithium, Tolsa SA of Spain in sepiolite, and Etibank of Turkey and US Borax of the USA in borates.

PRICES

A major influence in the mineral industry was the need to survive in the face of declining commodity prices in terms of real dollars. The US Geological Survey computed the US mine production composite price index based on data for five metal commodities (copper, gold, iron ore, lead, zinc) and seven industrial mineral commodities (cement, clay, crushed stone, lime, phosphate rock, salt, sand and gravel). During 1997, these commodities accounted for more than 85 percent of the value of metal and industrial mineral mine production in the United States. Overall, the trend of inflation-adjusted prices shown in the composite index declined. The use of mineral materials in the United States increased throughout the 20th century but the price trend was down as the result of adequate sources of supply, competition, and reduction in the costs of production.

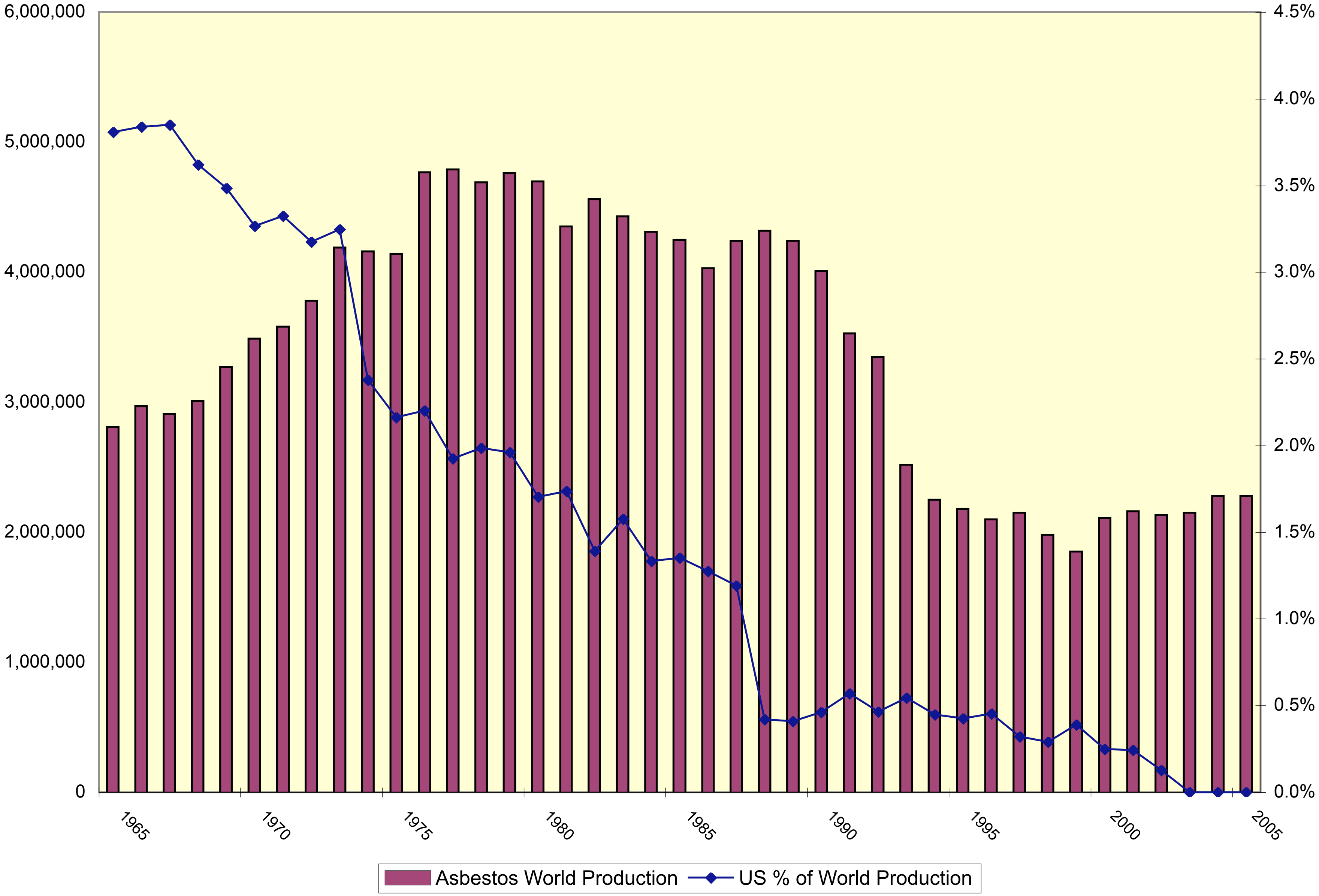
SUMMARY

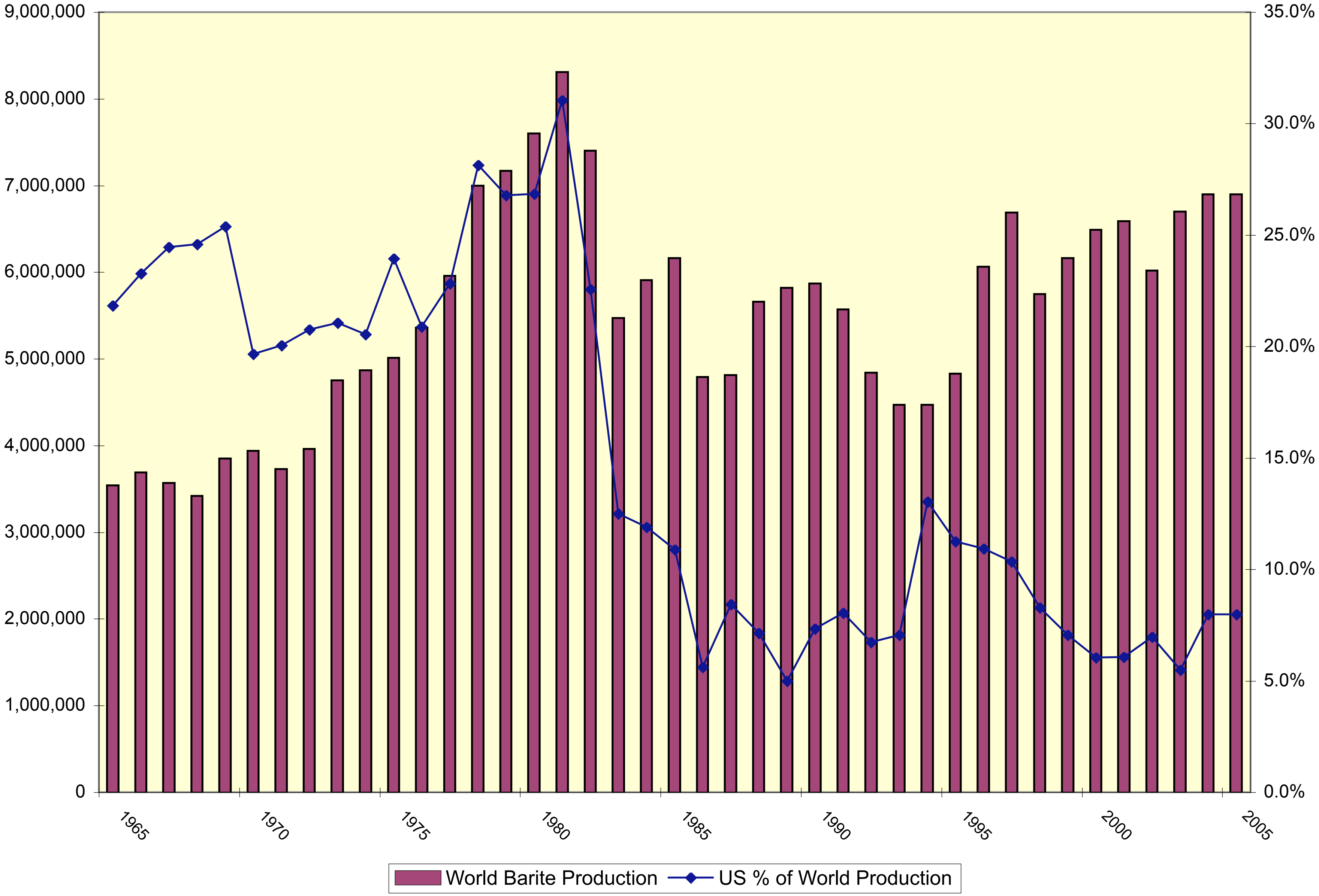
The past quarter century has seen the demand for industrial minerals increase in volume and shrink in price. Fewer but larger companies compete in a more sophisticated industry where quality control and efficiencies are essential for survival. Consuming industries have relied on mineral producers to provide better quality grades at lower prices, and suppliers have responded with the development of value-added grades designed to remain competitive and service new markets. Some traditional markets have disappeared and new one open up, and the traditional centers of production and/or consumption have shifted to follow the “Made in China” and similar labels.

Appendix: Timeline and Mineral Production Figures

		1965	1st Forum on the Geology of Industrial Minerals (FGIM), Columbus, OH. Period (1960s) when manganese production from Groote Eylandt, Australia, and Moanda, Gabon, begins.
		1966	High-strength rare-earth cobalt magnets discovered enabling miniaturization of many electronic devices
		1967	*Industrial Minerals* launched and Sgt. Pepper released.
		1968	
		1969	Bertrandite produuction started in Utah. Strontium replaced barium in color television faceplate glass to block X-ray emissions.
		1970	Clean Air Act in USA was passed requiring control of SO2 emissions and the increased use of lime. Antimony-based flame retardants were developed.
		1971	Opposition to the use of asbestos began, causing a downward spiral in sales. Color television faceplate glass became the dominant end use for strontium. Effects of inflation rates, increased energy costs, and additional costs associated with complying with air emission standards results in increased prices of some commodities.
		1972	Potential use of lithium in batteries discussed followed by price recovery.
	🟥	1973	OPEC oil embargo. Phaseout of lead in gasoline began under the Clean Air Act.
Increased energy costs and rapid inflation boost prices (1974 - 79)	🟥	1974	1st *Industrial Minerals* Congress, London
	🟥	1975	Catalytic converters became required equipment in automobiles in the USA (encoraging the use of talc and kaolin for the substrate).
		1976	2nd *Industrial Minerals* Congress, Munich
		1977	
		1978	3rd *Industrial Minerals* Congress, Paris
	🟥	1979	Economic recession & high inflation (1979 - 81). Beryllium metal price set by one producer.
	🟥	1980	Adoption of steelmaking technology that significantly reduces amount of manganese required per ton of steel produced (1980s).4th *Industrial Minerals* Congress, Atlanta
	🟥	1981	
		1982	Recovered sulfur production, resulting from implementation of the Clean Air Act, surpassed that of Frasch for the first time. 5th *Industrial Minerals* Congress, Madrid.
		1983	Aluminum almost completely replaced steel in the beverage can market.
		1984	Lithium carbonate production began in Chile (Foote). 6th *Industrial Minerals* Congress, Toronto
		1985	U.S. environmental regulations limit lead in gasoline, reducing demand for rare-earth-containing petroleum fluid cracking catalysts.
		1986	Last US synthetic soda ash plant closed in Syracuse, NY. US domestic production of arsenic ceases. Rare-earth-containing ceramic superconductors were discovered (for which the Nobel Prize in physics was awarded in 1987).7th *Industrial Minerals* Congress, Monte Carlo
		1987	Montreal Protocol was adopted to phase out production of chloroflurocarbons. High-temperature superconductivity in Y-Ba-Cu-O compounds was discovered. Tight supply of magnesium because of increased aluminum consumption (1987-88).
		1988	Purchase of beryllium metal for the National Defense Stockpile (NDS).8th *Industrial Minerals* Congress, Boston.
		1989	Renison discovers mineral sands in Virginia.
	🟥	1990	Conversion of NDS beryl ore to beryllium metal for the NDS. Low-cost yttrium from southern China became widely available. 9th Industrial Minerals Congress, Sydney.
	🟥	1991	Dissolution of the Soviet Union. Open-hearth furnace steel production ended in USA. Phosphate mining ended in Tennessee. Clumping bentonite cat litter was introduced. Antidumping and countervailing duty investigations of magnesium imports into US from Canada initiated. Antidumping duties assessed on U.S. silicon metal imports.
		1992	*Industrial Minerals HandyBook* published. Price of cerium metal increased due to increased demand in automotive catalytic converters. 10th *Industrial Minerals* Congress, San Francisco.
		1993	The National Defense Authorization Act established new disposal targets for the national defense stockpile (mainly goals were reduced to zero). Phosphate mining ended in Montana. Antidumping duties assessed on U.S. ferrosilicon imports (1993-94).
		1994	Antidumping duty investigation initiated on US magnesium imports from China, Russia, and Ukraine. 11th *Industrial Minerals* Congress, Berlin.
		1995	Last US fluorspar mine closed in Illinois.
		1996	US Bureau of Mines closed. US production of chloroflurocarbons ceased leading to dramatic decrease in fluorspar consumption. Lithium carbonate production start up at Salar de Atacama, Chile (Minsal/SQM). 12th *Industrial Minerals* Congress, Chicago.
		1997	Start of the Asian financial crisis. Startup of lithium extraction from brine in Argentina (FMC).
		1998	Last US spodumene (lithium ore) mine closed - production moved to Chile. 13th *Industrial Minerals* Congress, Kuala Lumpur.
		1999	Consolidation in refractories; Imetal (Imerys) in acqisition mode.
		2000	Last U.S. Frasch sulfur mine closed because of low prices, high fuel costs, and technical problems. 14th *Industrial Minerals* Congress, Denver.
		2001	September 11 attacks. Palabora baddeleyite mine closes.
		2002	15th *Industrial Minerals* Congress, Paris
		2003	Start of strong econinic growth, especially in US and China. 16th *Industrial Minerals* Congress, Montreal.
		2004	17th Industrial Minerals Congress, Barcelona
		2005	USGS budget cuts. Commodity price recovery begins.
		2006	18th *Industrial Minerals* Congress, San Francisco; 42nd Forum, Asheville, NC; Zeolites '06, Socorro, NM; IMAR7 published

World Production Chart 1

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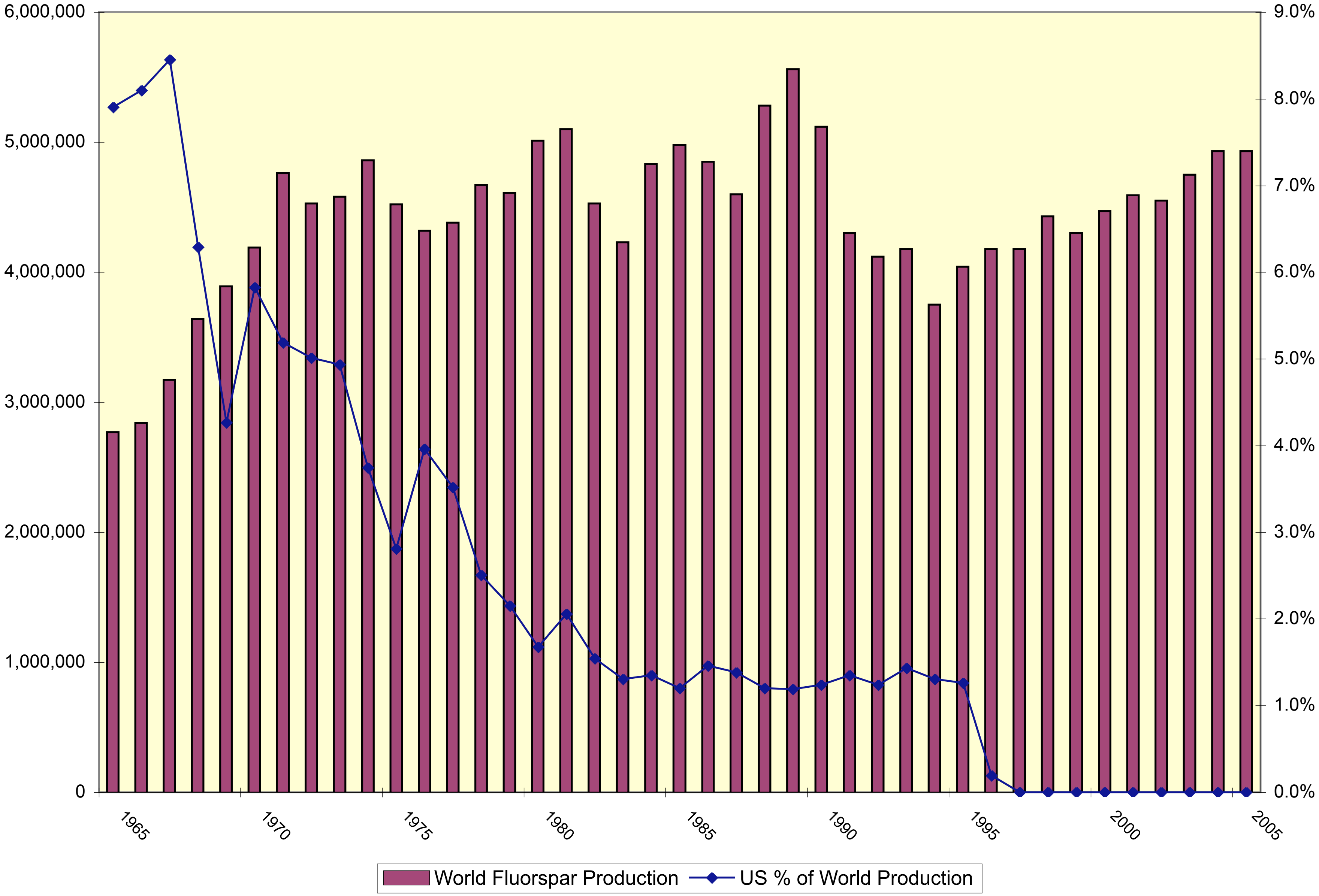
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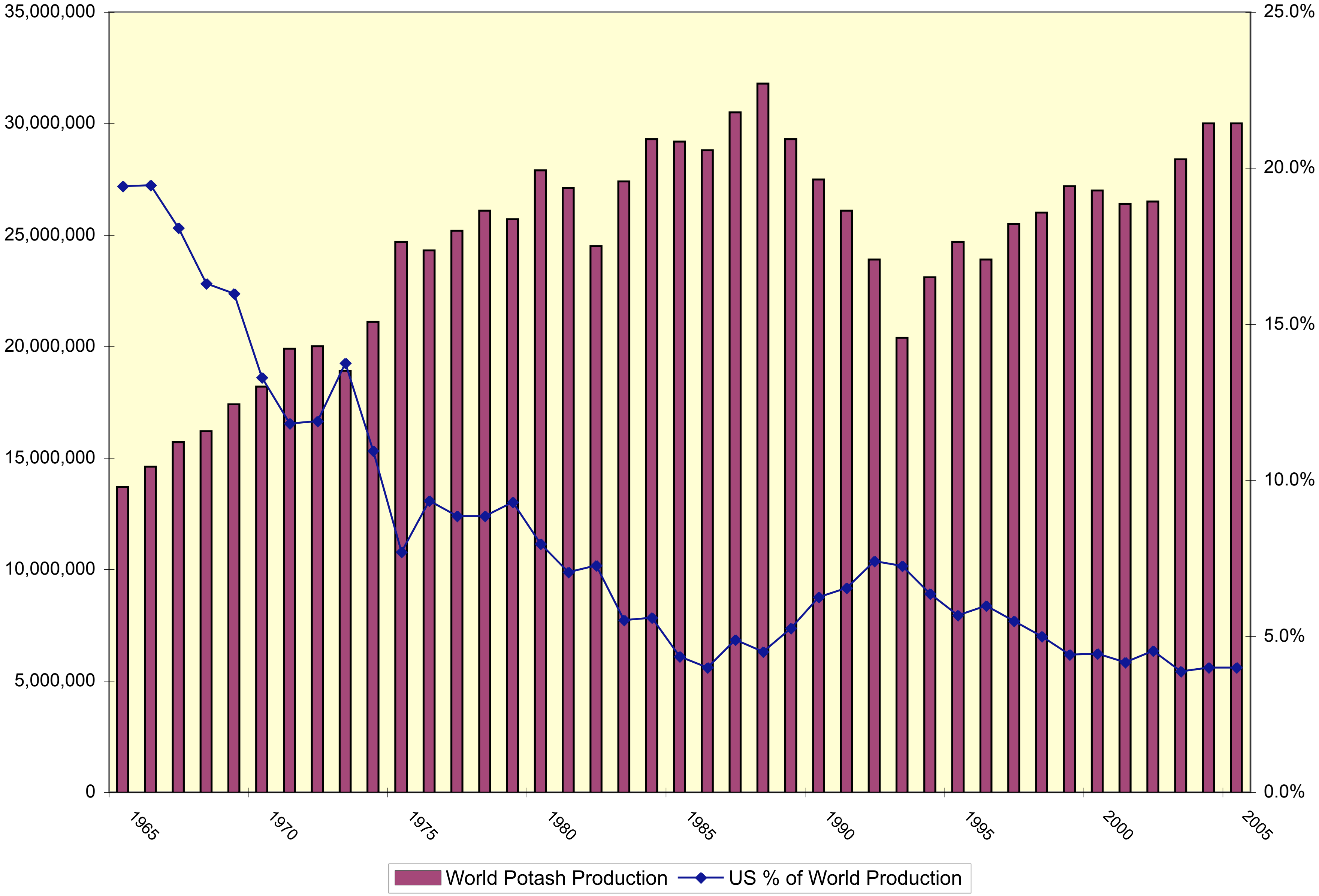

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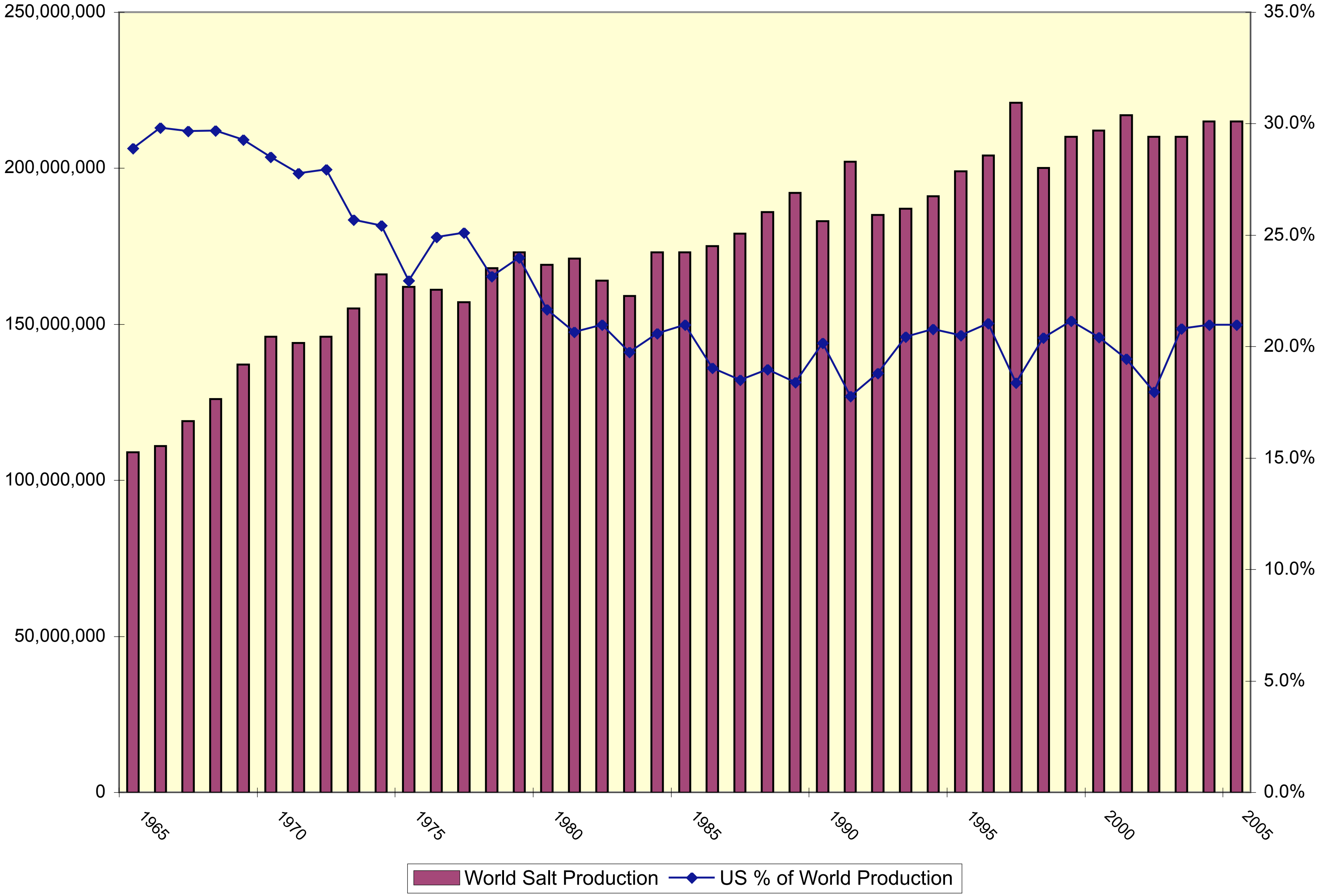
US % of World Production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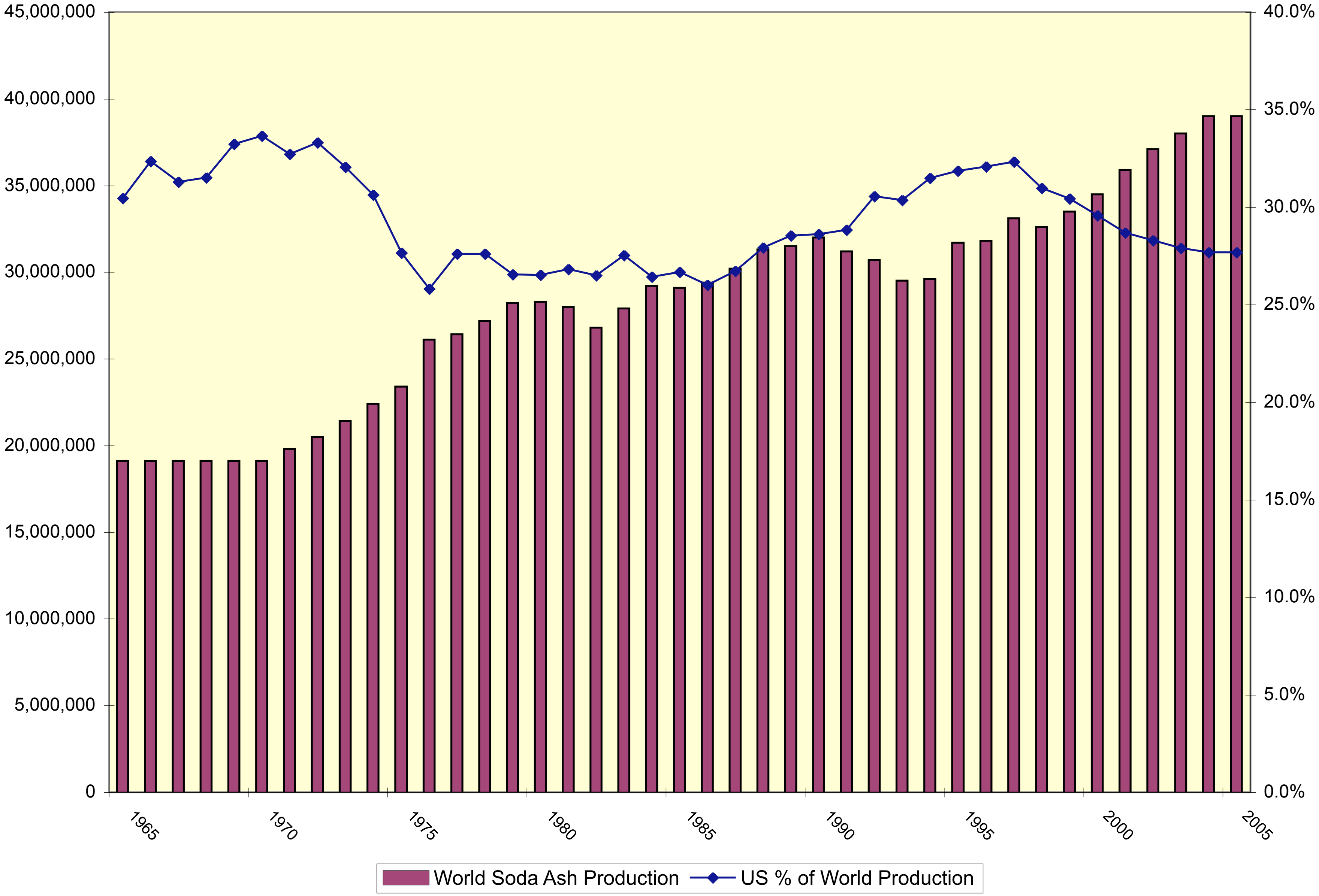
US % of World Production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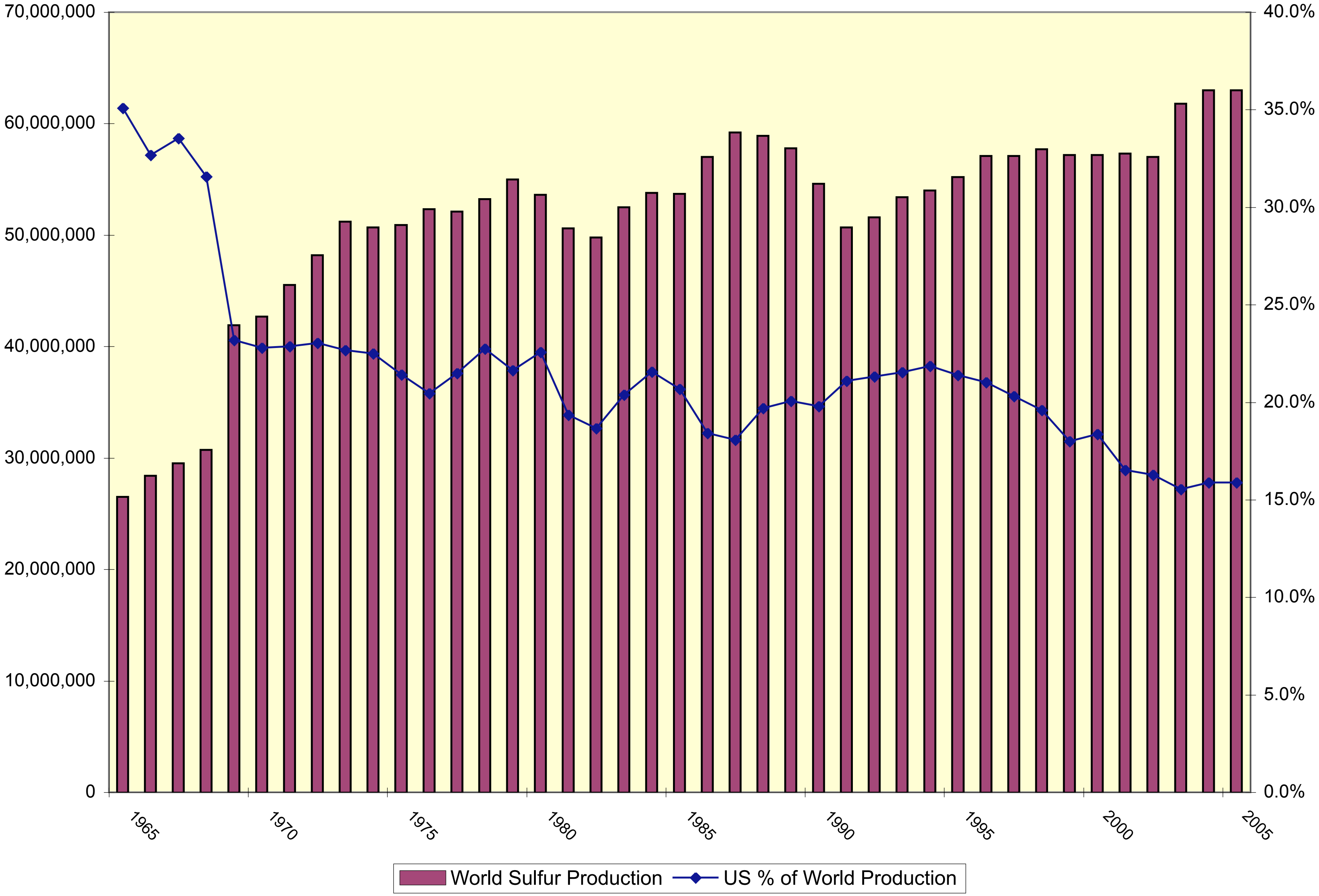
World Soda Ash Production
US % of World Production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1970
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1980
1985
1990
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2000
2005
World Sulfur Production
US % of World Production

Environmental and Economic Factors Influencing Use of Mineral Admixtures in Concrete Over the Last 25 Years

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ABSTRACT

The cement industry remains one of the most energy-intensive industries even after efficiency measures implemented over the last 25 years. The energy crisis of 1973 forced changes in the type of fuel used at many cement plants and increased energy efficiency. Many cement plants switched to coal in the late 1970s and early 1980s. Since 1980, there has been a gradual trend away from inefficient wet kilns to dry kilns. The 1990 Clean Air Act Amendment set limits on emissions and forced capital outlay for dust collection devices at cement plants. The U.S. Bureau of Mines estimated meeting the requirements of this act would account for 20 to 25 percent of capital expenditures for new cement plants and major additions to existing plants. In the 1990s, use of alternative fuels such as shredded tires and hazardous waste further changed the fuel mix.

Burning limestone and other raw materials to produce clinker during cement manufacture releases CO_2 second only to that of iron and steel production. As global warming becomes of greater concern, the cement industry must further reduce emissions of CO_2 and other noxious gases.

In the past 20 years, sustainable development has brought social, environmental and energy efficiency concerns together with management and governance of natural resources. The concrete and cement industries now use more byproducts including artificial pozzolans and supplementary cementitious materials (SCMs). Natural pozzolans have been used for centuries but only recently have fly ash, silica fume, and blast furnace slag found widespread use. They replace part of the portland cement in concrete or a portion of the clinker in blended cements.

INTRODUCTION

The use of natural pozzolans for masonry and cement construction dates back to ancient Rome. The term pozzolan comes from the deposits of trachyte tuff near the town of Pozzuoli (Italy). Romans used pozzolanic tuff in conjunction with lime to form cement for many of their large building projects. They found that the addition of the pozzolan created a sea water resistant concrete that would harden under water. Today volcanic tuff and pumicite remain in use as pozzolans throughout the world and are commonly called pozzolana in the literature. Pozzolans are siliceous or siliceous aluminous materials that alone possess little or no cementitious value that will, in a finely divided form and with water, chemically react with cement at ordinary temperatures to form compounds with hydraulic cementitous properties. Supplementary cementitous materials (SCMs) are finely divided, non-crystalline or poorly crystalline materials similar to pozzolans. They possess latent cementing properties that become active in the presence of portland cement and water (Malhotra and Mehta, 1996). Pozzolans can be natural or artificial;

primarily artificial pozzolans are those formed as a byproduct of some industrial process such as fly ash, but can include calcined shales and clays. SCMs include ground, granulated blast furnace slag (GGBFS), and high-calcium fly ash. Although Class F fly ash and silica fume are not strictly supplementary cementitious materials, but they are often grouped with GGBFS and Class C fly ash in industry literature as SCMs. Pozzolans and SCMs are called mineral admixtures when added to concrete or blended cements.

Portland cement replaced the early pozzolanic cements shortly after its invention in 1824 because of a faster setting time and better early strength than the pozzolan-based cements. The construction boom after World War II significantly increased the use of portland cement throughout the country in major construction projects, such as dams and highways. Natural pozzolans were added to the concrete in many of the dams built in the western U.S. through the 1960s and fly ash use is documented from the 1940s. By the early 1980s, the cement industry was dealing with the continued effects of the energy crisis of 1973, including short supply and high costs, increased environmental regulations, economic recession and other economic factors. One way of lowering costs was by using pozzolans.

ENERGY EFFICIENCY

Fuel

The 1973 Arab oil embargo and the Iran-Iraq war (1980–1988) increased costs and limited natural gas supplies, prompting cement plants to convert their kiln systems from natural gas to coal and petroleum coke. From 1972 to 1994, coal and coke went from 36 percent to 74 percent of the gross fuel mixture at cement plants. Natural gas usage dropped from 45 percent to 7.2 percent during the same period (American Portland Cement Alliance, 1997). By 1990, energy costs for producing cement accounted for 30 percent–45 percent of the total production costs with coal as the major fuel consumed (Pitcher, 1990). Table 1 shows fuel consumption from 1980-2005 (van Oss and Padovani, 2003; van Oss, 2002, 2003, 2004, 2005). Coal continues to be the main fuel for the cement industry followed by petroleum coke (Table 1).

Table 1. Fuel Consumption for U.S. cement industry. Adapted from van Oss, and Prodovoni and van Oss, 2002, 2003, 2004, 2005, Table 7).

Fuel consumption	**1980**	**1985**	**1990**	**1995**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Coal (kMt)	10,601	10,087	9,098	8,241	9,066	9,206	10,095	10,240	9,690	9,460	9,660	9,490
Coke from coal (kMt)[1]	nd	nd	nd	455	432	343	442	420	17	3	0	0
Petroleum coke (kMt)	488	442	379	1,475	1,197	1,622	1,351	1,370	1,910	1,980	2,260	2,350
Fuel Oil (ML)	653	120	299	42	73	134	124	93	93	85	105	87
Natural gas (Mm^3)	1,718	301	294	1,069	720	653	338	397	479	377	396	395
Tires (kMt)	nd	nd[2]	nd[2]	158	269	685	374	300	304	387	377	405
Other solid waste (KMt)	nd	nd[2]	nd[2]	68	74	816	1,016	320	112	317	125	130
Liquid waste (ML)	nd	nd[2]	nd[2]	885	1,268	905	929	829	962	910	997	1,470
Clinker output (kMt)	63,341	60,941	64,356	71,257	75,842	77,337	79,656	79,979	82,959	83,315	86,658	87,405

[1] Years labeled "nd" may be included in data for coal.

[2] Waste fuel data not collected until 1993, but fuels were being consumed beginning in the 1980s.

With the switch to coal as a primary fuel source, some cement companies began developing or leasing coal properties in the late 1970s (Dikeou, 1979). In New Mexico, Amcoal, a wholly owned subsidiary of Amcord, purchased a coal mine near Gallup in 1975 to provide coal to their cement plant in Phoenix, Arizona (Nickelson, 1988).

By the late 1980s, waste fuel was becoming another inexpensive energy source for cement companies to cut the fuel costs. The Portland Cement Association reported that 38 percent of the cement plants were using waste fuel by 1991 (Solomon, 1991). Waste fuels are classified as hazardous and non-hazardous. Hazardous waste includes printing inks, dyes, paints, solvents, chemicals, and plastics. Non-hazardous wastes include scrap tires, some medical waste, used oil, municipal wastes, and non-hazardous plastics and chemicals. Because the clinker process requires high temperatures, long burning times, and high turbulence, cement kilns offer a satisfactory way to dispose of these materials and capture their energy. Some conversion must take place to accept these fuels but the cement company often receives compensation for taking this material (Solomon, 1992). Table 1 shows the increased use of tires, other solid waste, and liquid waste from 1995 through 2005; no data are available before 1993 for these fuels (van Oss and Padovani, 2003). Liquid waste was the third largest fuel source for the cement industry in 2005.

Processes

Other changes to increase energy efficiency at cement plants included shutting down or converting older plants that employed the wet kiln process to more efficient dry process units. By 1984, wet kiln clinker capacity was down to 45 percent of total capacity. Cement clinker produced from wet kilns declined to 29 percent in 1994 and 13.5 percent in 2005 (van Oss, 2005). Many of the newer individual dry kilns have much larger capacities, greater than 600,000 st (454,000 mt) clinker annually, replacing several of the older wet kiln units (Singleton and Davis, 1980). No new wet kilns were constructed in the U.S. or Canada after 1975 (Table 2, The Portland Cement Association, 1992).

Table 2. Age and capacity of existing kilns in thousand metric tons (U.S. Environmental Protection Agency, 1993, adapted from Portland Cement Association, 1992).

	Wet Kilns		**Dry Kilns**		**Kilns Overall**	
Date of Kiln Installation	Number of Kilns	Average Capacity (KMt)	Number of Kilns	Average Capacity (KMt)	Number of Kilns	Average Capacity (KMt)
After 1980	0	0.0	26	690.3	26	690.3
1976-1980	0	0.0	18	653.1	18	653.1
1971-1975	11	459.6	32	476.8	43	470.9
1966-1970	13	424.9	19	425.0	32	426.9
1961-1965	20	355.4	38	336.1	58	346.3
1956-1960	19	260.5	46	199.6	65	226.7
1951-1955	5	193.6	19	176.6	24	181.1
1946-1950	6	158.0	9	164.0	15	160.0
1941-1945	1	150.0	0	0.0	1	150.0
1936-1940	1	153.0	2	138.0	3	143.0
1931-1935	0	0.0	0	0.0	0	0.0
Before 1931	4	159.3	0	0.0	4	159.3

Other upgrades to plants included grinding and crushing of raw materials in the preheater and recalciner systems. Precalciners and preheater kilns have advantages over dry and wet kilns; the feed is more uniformly calcined and operating conditions are easier to control (U.S. Environmental Protection Agency, 1993). Precalciner kilns greatly reduce the residence time needed for raw materials to become clinker and reduce the required heat load in the rotary kiln. The overall energy efficiency of producing cement is significantly improved by adding a preheater or precalciner. Table 3 shows the typical energy requirements for the different kiln types. By 1985, 59 suspension and 18 grate preheaters were in operation at U. S. cement plants (Johnson, 1985). Cement plants also consume energy outside the clinker process generally as electricity. However, electricity use has remained nearly constant since 1990, increasing only as production increased (Jacott, Reed, Taylor, and Winfield, 2003). The estimated energy efficiency, amount of energy needed per ton cement produced, in 1990 was 5.06TJ/kMt (terajoules per thousand metric ton) and 5.36TJ/kMt in 2001(Jacott, Reed, Taylor, and Winfield, 2003). By 2005, the average energy consumption of wet and dry plants combined was 4.9 GJ/mt (van Oss, 2005). In summary, even with the switching of fuels and all the kiln upgrades over the past 25 years, the cement industry remains an energy intensive industry.

Table 3. Energy consumption by kiln type calculated per ton of portland cement. From Worrell, Price, Martin, Hendriks, and Ozawa Meida, 2001.

Kiln Type	Energy Consumption (GJ/t)
Wet	5.9-7.0
Long dry	4.2
Short dry, suspension preheating	3.3-3.4
Short dry, preheater and precalciner	2.9-3.2

GOVERNMENTAL REGULATIONS

Several governmental regulations have encouraged the use of artificial pozzolans, particularly those that are byproducts of industrial processes. Many of these regulations promote ways of recycling these materials as an alternative to disposal in landfills.

RCRA and Amendments

As of 1976, the Resource Conservation and Recovery Act (1976) gave the U.S. Environmental Protection Agency (EPA) authority to control hazardous wastes from “cradle-to-grave,” including generation, transportation, treatment, storage, and disposal. The act also put in place a framework for management of non-hazardous wastes. Through the Bevill Amendment to RCRA (1980), Congress exempted several types of fossil fuel combustion wastes, including fly ash, from Subtitle C, which imposes obligations on those who generate, store, transport or dispose of hazardous wastes. Coal combustion materials fall under the jurisdiction of individual states under Subtitle D for disposal of solid wastes, whether they are recovered for use or disposed in a landfill. In 1993, EPA issued its final regulatory decision and continued the exemption of fly ash as a hazardous waste.

In 1983, the EPA implemented federal procurement guidelines for cement and concrete containing fly ash to encourage utilization of fly ash. Comprehensive Guidelines for Procurement of Products Containing Recovered Materials (CPG) was issued by the EPA May 1, 1995. These guidelines consolidated five previous procurement guidelines, one being fly ash, and designated 19 items that are or can be made with recovered materials. In addition, the Recovered Materials Advisory Notice (RMAN) contains the EPA's recommendations to procuring agencies for meeting their RCRA obligations with respect to the existing and newly designated items. The pertinent EPA recommendations in RMAN are:

a) Revising procurement programs for cement and concrete or construction projects involving cement or concrete to allow the use of coal fly ash and GGBFS as appropriate.
b) Procurement agencies include provisions in construction contracts to allow for the use, as optional or alternative materials, of cement or concrete containing coal fly ash or GGBFS, where appropriate.
c) Procurement agencies review and revise performance standards to ensure they do not arbitrarily restrict the use of GGBFS unless the restriction is justified on an individual job basis for documented technical reasons (Federal Highway Administration, February 1996).

Under RCRA, procuring agencies, including federal state or local agencies using appropriated federal funds and spending more than $10,000 a year on an item are required to purchase an EPA-designated product that contains recovered materials. As part of the Energy Policy Act of 2005 the U.S. Congress instructed the EPA and other agency heads to give priority to achieving greater use of recovered mineral components in cement or concrete projects for which these materials historically have not been used or only minimally used. This policy was to be implemented by August 10, 2006. As part of this legislation, a 30-month mineral recycling study will look at the use of recovered minerals (American Coal Ash Association, March 2006).

Intermodal Surface Transportation Efficiency Act (ISTEA)

The ISTEA (1991) authorized $155 billion to be spent over 5 years to help rebuild the nation's infrastructure. This act gave high priority to research on recycling. Through ISTEA, the Federal Highway Administration and the National Cooperative Highway Research Program sponsored several projects relating to recycling. This program resulted in at least two research projects dealing specifically with use of SCMs to enhance the durability of concrete bridge decks. To implement the ISTEA the Federal Highway Administration created the High Performance Concrete Technology Delivery Team in 1997. The team's purpose is to motivate and help state departments of transportation build more economic and durable bridges using high performance concrete. Artificial pozzolans and SCMS are major components of this type of concrete.

INDUSTRY CHANGES

Cement Company Structure

The Federal Trade Commission (1985) removed the ruling preventing vertical integration in the construction materials industries. With this change, the cement industry began actively acquiring companies that are dependent on cement, such as ready-mix concrete and construction businesses. Cement companies also began buying companies that produce or sell products crucial to cement making, such as crushed stone, and purchasing or developing companies marketing SCMs or artificial pozzolans. In part, the intent of vertical integration is to secure a supply of fuel and other materials and improve efficiency in supplying product to customers. Many of the large cement companies have marketing divisions for mineral admixtures such as fly ash and GGBFS. These companies include St. Lawrence, Lone Star, Carolinas Cement, Lafarge, Holcim, Holnam, and Salt River Materials Group (formerly Phoenix Cement).

Concrete Methods

During the 1980s and 1990s, research of artificial pozzolan applications was on the rise. The U.S. Bureau of Mines (Phillips, 1981) ran tests to replace a portion of the portland cement in mine backfill with pozzolan (fly ash) and lime. Compressive strength analyses on 84 samples serve as examples for the best backfill mix for any mine. This application benefits waste-disposal problems of fly ash and serves as a partial substitute for portland cement to reduce the costs of backfilling. Malhotra and Mehta (1996) describe in detail the major mineral admixtures and the beneficial properties of pozzolans and SCMs when used concrete. They also outlined the standard U.S. and Canadian specifications for these materials for use in portland cement concrete.

Roller-compacted Concrete

The high cost of cement and moving and placing mass concrete in dam construction are problematic when building gravity dams. Constructing dams became easier and more cost effective using roller compacted concrete (RCC), a stiff concrete that can be placed by asphalt paving equipment. The first RCC dam was built in Japan in 1980. Shortly after this, the U.S Bureau of Reclamation (BOR) used RCC in constructing Willow Creek Dam near Hepner, Oregon. The cost per cubic foot for conventional mass concrete was $65 compared to $18.93 per cubic yard for the RCC used at Willow Creek Dam in 1982 (Schrader, 1982) . The BOR has constructed and repaired many dams using RCC because of its economy, performance and speed of construction. RCC often consists of a cement-pozzolan mix. Pozzolans are a common additive because of the reduced cost and lower heat generation. Pozzolans also replace aggregate fines in the mixture.

In 1987, the BOR built the Upper Stillwater Dam in eastern Utah using 40 percent portland cement and 60 percent fly ash (Moore, 1995). Malcolm Dunstan & Associates maintains a RCC dam website with a database listing of 39 dams for the U.S.; 25 dams have Class F fly ash as a portion of the cementitious material and two have Class C fly ash. Construction for these gravity dams took place from 1982 through 2006 (Malcolm Dunstan & Associates, 2007). No RCC dams in the U.S. are listed as having natural pozzolans, ground-granulated blast furnace slag (GGBFS), or a mixture of GGBFS and fly ash as part of the cementitious material. RCC dams in South America, Mexico, Greece, and Vietnam use natural pozzolans. Many dams in Brazil, Turkey, Japan, and South Africa include GGBFS in the concrete mixture.

High Performance Concrete

High performance concrete (HPC) technology started in France in 1980. As part of the Strategic Highway Research Program (1987), HPC technology came to the U.S. in 1989. HPC is defined by the American Concrete Institute as concrete that meets special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices (Federal Highway Administration, 2007). Properties of HPC include ease of placement, high early strength, impermeability and high density, durability and toughness, long service life (≥ 75 years), low heat of hydration, minimal shrinkage or thermal expansion, flowability, and self leveling. Mineral admixtures are necessary to achieve many of these requirements. A typical HPC today can contains 5 percent–15 percent silica fume, 50 percent–65 percent GGBFS, and up to 50 percent fly ash (McCraven, 2002). Silica fume adds strength and durability, while fly ash and GGBFS give better finishability, decreased permeability, and increased resistance to chemical attack. Although HPC can be double the cost of regular concrete, the extended service life and lower maintenance costs reduce the overall cost of the concrete structure. In 1993, as part of the ISTEA, the Federal Highway Administration (FHWA) initiated a national program to use HPC in bridges. The FHWA launched a quarterly newsletter (1999) called Bridge Views, developed through the Strategic Highway Research Program (SHRP), to transfer implementation technology for HPC to companies and state agencies.

USE OF ARTIFICIAL POZZOLANS AND SCMS

Increased interest in mineral admixtures, particularly fly ash and iron and steel slag, began in earnest in the late 1970s to early 1980s because of the cost savings they would pass on to the finished product. Several government regulations promoted the use of artificial pozzolans particularly in government-funded projects. Because these admixtures come from distinct industrial processes, different factors have influenced their development and use. For details on the production and specifications for these artificial pozzolans and SCMs, see Hoffman, 2006.

Fly Ash

As a major consumer of portland cement, the U.S. Bureau of Reclamation (BOR) has been at the forefront in design and construction of concrete dams. Early in the 20th Century, the BOR added natural pozzolans to concrete used in their dams partly as a cost-saving measure. BOR engineers also recognized that adding pozzolans reduced the temperature rise in mass concrete, decreasing the potential for cracking (Dolen, 2002). Because most of the BOR operations are in the western U.S., they had a ready supply of natural pozzolans from volcanic deposits (pumicite) and from diatomite deposits in California and Nevada. Several early dams built from the 1940s through the 1960s had natural pozzolans as a component in the concrete. The BOR was instrumental in developing the technologies to incorporate fly ash, an end product of coal combustion, into concrete (Manz, Pflughoeft-Hassett, 2005) and began using fly ash on a regular basis in the 1970s in dam construction to offset cement shortages.

In an effort to promote use of fly ash in cement and concrete, the EPA issued guidelines in 1983 for purchasing cement containing fly ash. In 1986, the Federal Highway Administration published “Fly Ash Facts for Highway Engineers” (Boles, 1986). This publication promotes the use of fly ash as a pozzolan in concrete and provides basic technical information about applications of fly ash in highway construction. This publication is now in its fourth edition, with new applications and updates from the original because of the increased use and new applications of fly ash in highway construction (American Coal Ash Association, 2003)

Restrictions on SO_2 emissions of the Clean Air Act Amendment (1990) required many electric utilities either to switch to low-sulfur coal or to add SO_2 scrubbers. There are two scrubber systems in use, wet and dry. A wet scrubber produces a flue-gas desulfurization material and has no effect on the fly ash. A dry scrubber system placed in line before the fly ash collection system creates fly ash coated with desulfurization byproducts ($CaO + CaSO_4$) that cannot be used as a pozzolan in concrete. The Clean Air Act Amendment of 1990 also required reductions in NO_x emissions from coal-fired power plants. One method of reducing NO_x involves injecting ammonia into the exhaust gas, which can result in high levels of ammonia in the fly ash (up to 2500 ppm). At ammonia levels greater than 100 ppm, the ash is unmarketable as a pozzolan for concrete owing to the strong ammonia odor when poured. Technologies are being developed to remove ammonia from fly ash to meet specifications as a pozzolan. One method would chemically induce the ammonia from the fly ash at ambient temperatures (Gasiorowski, Bittner, and Hrach, 2001).

Another method of lowering NO_x emissions is by retrofitting coal-fired boilers with low-NO_x modifications. Depending on the coal, more unburned carbon (LOI) can end up in the fly ash. Specifications for fly ash as a pozzolan limit the percent LOI, and the extra unburned carbon from the low NO_x burner can make the fly ash unusable as a pozzolan (Schwartz, 2003). Lowering the percent LOI in fly ash and finding uses for fly ash with higher LOI content have been the subject of many papers presented at conferences on unburned carbon initiated by the National Energy Technology Laboratory (NETL) since 1995.

In 2002 EPA created the Coal Combustion Products Partnership—C^2P^2. The partnership is a cooperative effort between the EPA, American Coal Ash Association, Utility Solid Waste Activities Group, Department of Energy, and the Federal Highway Administration. The consortium promotes the beneficial use of coal combustion products, including fly ash, and the environmental benefits of their use. One goal is to increase the use of fly ash as a mineral admixture in concrete by 50 percent to 18.6 million tons (16.87 million mt) in 2011. By meeting this goal, greenhouse gas emissions not emitted by reduced cement production would be 5 million tons (4.54 million mt; U.S. Environmental Protection Agency, 2002).

In March 2005, the EPA issued the Clean Air Mercury Rule (CAMR) to permanently cap and reduce mercury emissions from coal-fired power plants. This rule established "standards of performance" limiting mercury emissions from new and existing utilities and created a market-based cap-and-trade program that will reduce nationwide utility emissions of mercury in two phases. In phase one, in place by 2010, reducing emissions will take advantage of mercury reductions achieved while reducing SO_2 and NO_x setting a cap of 38 tons, which would be a 20 percent-30 percent reduction in U.S. mercury emissions. In the second phase, due in 2018, utilities would be subject to a second cap that will when fully implemented, reduce total mercury emissions to 15 tons. New coal-fired power plants constructed on or after January 30, 2004 have to meet new performance standards and are subject to these mercury emission caps. Under the CAMR, each state has a mercury emission budget based on these caps.

One method of capturing more mercury is by introducing activated carbon into the flue gas and collecting this carbon with the fly ash. By adding activated carbon, the fly ash may be unmarketable as a pozzolan. Carbon as an organic is detrimental to air-entrainment chemicals used in concrete (Schwartz, 2003).

GGBFS

In 1982, Atlantic Cement began operation of a granulating and grinding plant to process slag from the adjacent Bethlehem Steel Sparrows Point plant in Maryland (now owned by Lafarge). The plant has the capability to consume approximately 800,000 st (735,748 mt) annually of water-granulated blast-furnace slag and reportedly uses six times less energy than that required to manufacture portland cement. The comminuted product is blended with portland cement or added as a separate component to the concrete mix. By 2001 there were more than a dozen plants producing GGBFS with a capacity greater than 2.5 million tons (2.27 million mt) per year (Hogen, Meusel, and Spellman, 2001). In the same year, the Slag Cement Association was established to educate and promote use of this material. GGBFS are included in the National Institute of Standards and Technology study, Building for Environmental and Economic Stability and recommended by the U.S. Green Building Council's Leadership in Energy and Environmental Design know as the LEED program.

Silica Fume

Interest in silica fume, a byproduct in the manufacture of ferrosilicon, started in the 1980s to utilize its properties that create a high-strength concrete appropriate for use in high-rise building construction. Silica fume in concrete also adds high durability and resistance to sulfate attack. When construction of high-rise buildings decreased in the early 1990s, the demand for silica fume slowed. Another use for silica fume is in parking structures and bridge decks. The Silica Fume Association was formed in 1998 to promote the benefits of silica fume and provide technical information about this product. Silica fume output is limited and producers are concentrated in the eastern U.S. It is sold as a value-added product in the U.S. for making high-compressive-strength concrete. In August 2001, the EPA proposed designating cement and concrete containing silica fume as meeting requirements for RCRA. In 2004, EPA amended the CPG to include concrete containing silica fume.

Terminology and Reporting

By the early 1990s, the term SCMs began appearing in the literature (Solomon, 1991) and mineral admixtures were becoming increasingly important to the concrete industry. However, pozzolan and SCM-based blended cements are only a small portion of the U.S. cement market in contrast to their popularity in European markets. The preferred method of using pozzolans or SCMs in the U.S. is by adding them to the concrete mix in specific proportions.

Because blended cements are a small portion of the pozzolan consumption in the U.S., reporting individual pozzolan usage either by the concrete industry or by pozzolan/SCMs marketers was not historically done through the U.S. Bureau of Mines and later the U.S. Geological Survey. Trade organizations for the different pozzolans and SCMs keep track of consumption and use for many of these products. End-use categories vary for the different pozzolans in the available statistics. The iron and steel slag commodity summary (U.S. Geological Survey, 2007) report GGBFS as a cementitious additive. Pumice and pumicite use as pozzolans are reported as a concrete admixture and aggregate. Pozzolanic use of diatomites is grouped with several other applications in the commodity summary. Consumption of silica fume, called microsilica in the Silicon Minerals Yearbook, is reported under miscellaneous and unspecified with silicon product (Corathers, 2005.)

Before 1998, the U.S. Geological Survey (and previously U.S. Bureau of Mines) did not differentiate GGBFS from other blast furnace slag and grouped fly ash with bottom ash as raw materials used in cement. Blended cements prior to 1998 were grouped together as portland slag and portland pozzolan (see Fig. 2). In the 1998 Minerals Yearbook report on cement (van Oss, 1998), raw materials used in producing clinker and cement were divided into fly ash, granulated blast furnace slag, natural pozzolans, and other pozzolans, which included microcrystalline silica and silica fume. Differentiating the blended cements by pozzolan type started in the 1998 Minerals Yearbook (van Oss, 1998). Separate reporting of these blended cements gave a better representation of the actual use of these materials in clinker and cement. Figure 1 shows production for several of the mineral admixtures used as pozzolans for the past 25 years. The pumice and pumicite data are plotted on the primary y-axis (left) and all other data are plotted on the secondary y-axis (right). Figure 2 shows the blended cement statistics. The secondary y-axis (right) in Figure 2 is associated with the total portland cement data only; all blended cement data are associated with the primary y-axis (left). Both figures illustrate the changes in reporting mentioned above and show the increased use of artificial pozzolans and a decrease in natural pozzolans usage. Blended cements represent a small portion of the total portland cement produced and shipped in the U.S. From 1998, the total blended cement produced increased from 0.97 percent of the total to 1.61 percent in 2004. In 2005, there was a significant increase in GGBFS blended cement, increasing the total blended cement to 2.59 percent of total portland cement shipped.

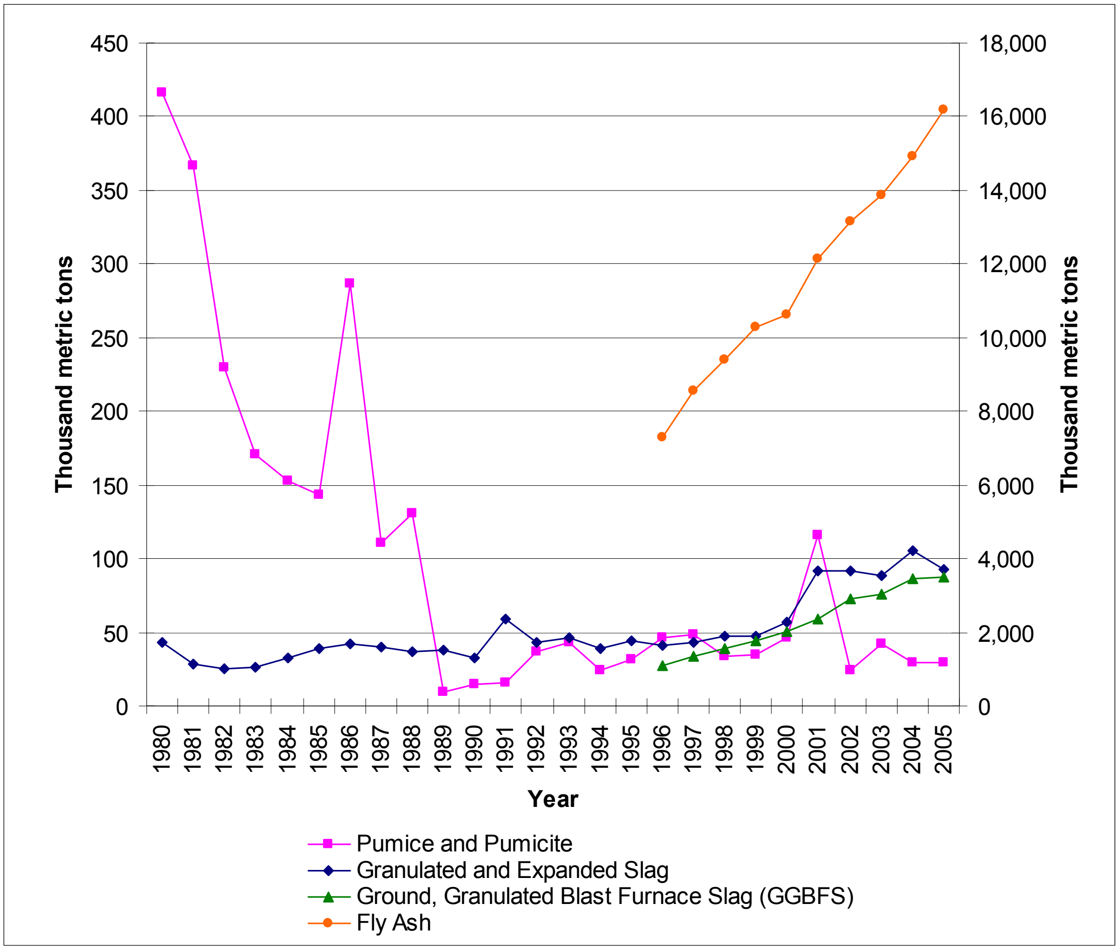

Figure 1. Pozzolan usage for cement and concrete. Pumice and pumicite plotted on primary y-axis, left; all other data plotted on secondary y-axis, right. (U.S. Geological Survey, 2005a, 2005b, and 2005c. Founie, 2004, 2005. Slag Cement Association, 2007, American Coal Ash Association, September 2006).

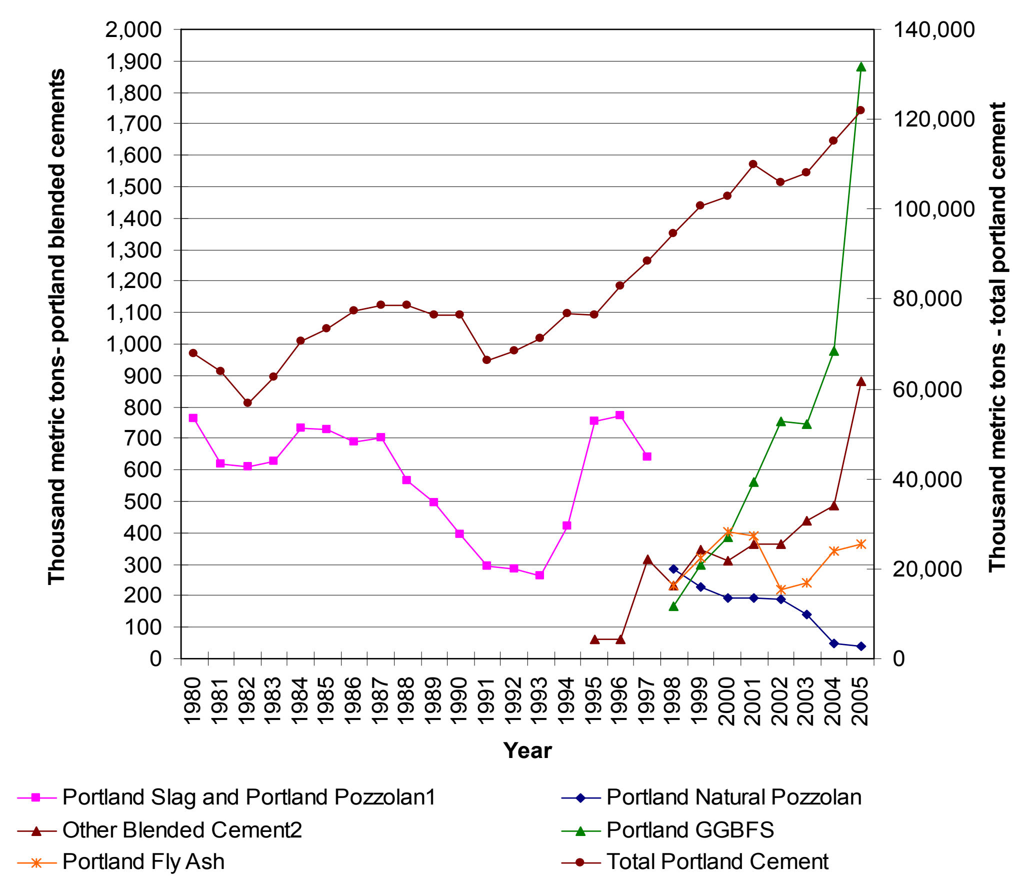

Figure 2. Total portland cement and blended cement shipped from plants in the U.S. to domestic customers. From Cement statistics in U.S. Bureau of Mines Minerals Yearbook 1980-1993, and U.S. Geological Survey Minerals Yearbook, 1994-2005. Total portland cement production is plotted on the secondary y-axis (right), all other production data are plotted on the primary y-axis (left).
[1] term not used after 1997
[2] Includes fly ash and silica fume, in 1998 includes CKD and silica fume

ENVIRONMENTAL FACTORS

Cement Kiln Dust

Beginning in the 1970s, the U.S. cement industry was required to install dust collectors for cement kiln dust, either in the form of bag houses or electrostatic precipitators. Cement producers must also meet water quality, noise, land use, health and safety requirements, which added to the cost of operations. In the 1990 Minerals Yearbook (Solomon, 1991), worries about restrictions on carbon dioxide, sulfur dioxide, and nitrogen oxide emissions from cement plants were triggered by the Clean Air Act amendments of 1990. The Bevill Amendment of RCRA mandated that EPA study cement kiln dusts and complete its Report to Congress by late 1993. The findings of this report found cement kiln dust (CKD) to have little or no environmental health risk, but did identify some groundwater contamination problems due to CKD mismanagement. In an associated regulatory determination, the EPA in January 1995 reaffirmed the 1993 findings and ruled that CKD was not a hazardous waste. In 2002, the EPA considered a new approach to CKD management and categorized it as a special waste, temporarily exempting it from federal hazardous-waste regulations. The EPA is developing standards for management of CKD (U.S. Environmental Protection Agency, 2007a). Concerns and added cost for the cement industry include monitoring of landfills, in particular groundwater, and controlling dust associated with CKD. The EPA also considers fossil fuel combustion wastes, including fly ash, as a special waste exempted from federal hazardous-waste regulations (U.S. Environmental Protection Agency, 2007b).

Emissions

Discussion of greenhouse gas emissions, CO_2 being the most common, began in earnest in the mid-1990s. Concerns for the cement industry included increased production costs to meet regulations, either by carbon taxes or through emission quotas, creating a competitive disadvantage to imports from countries lacking environmental regulations (van Oss, 1996). About one ton of CO_2 is emitted per ton of clinker produced translating to about 0.95 ton of CO_2 per ton of "straight" Portland cement (van Oss, 1997). The Energy Information Administration (EIA) collects data and calculates CO_2 emissions for different industrial processes. The EIA assumes an average lime content of 64.6 percent for cement clinker to calculate CO_2 emitted. Calculations are based on one molecule of $CaCO_3$ decomposing to one molecule of CaO and one molecule CO_2 (Energy Information Administration, 1994). Figure 3 illustrates CO_2 emissions from clinker production from 1987 to 2005. Clinker and ready mix concrete production are shown for comparison. Clinker production has increased 40 percent in this period along with a similar increase in CO_2 emissions. The cement industry is one of the largest sources of CO_2 emissions from industrial plants, other than iron and steel, but represents only about 1.5 percent of the U.S. total. Most of the CO_2 emissions come from power plants and motor vehicles (U.S. Environmental Protection Agency, 2001).

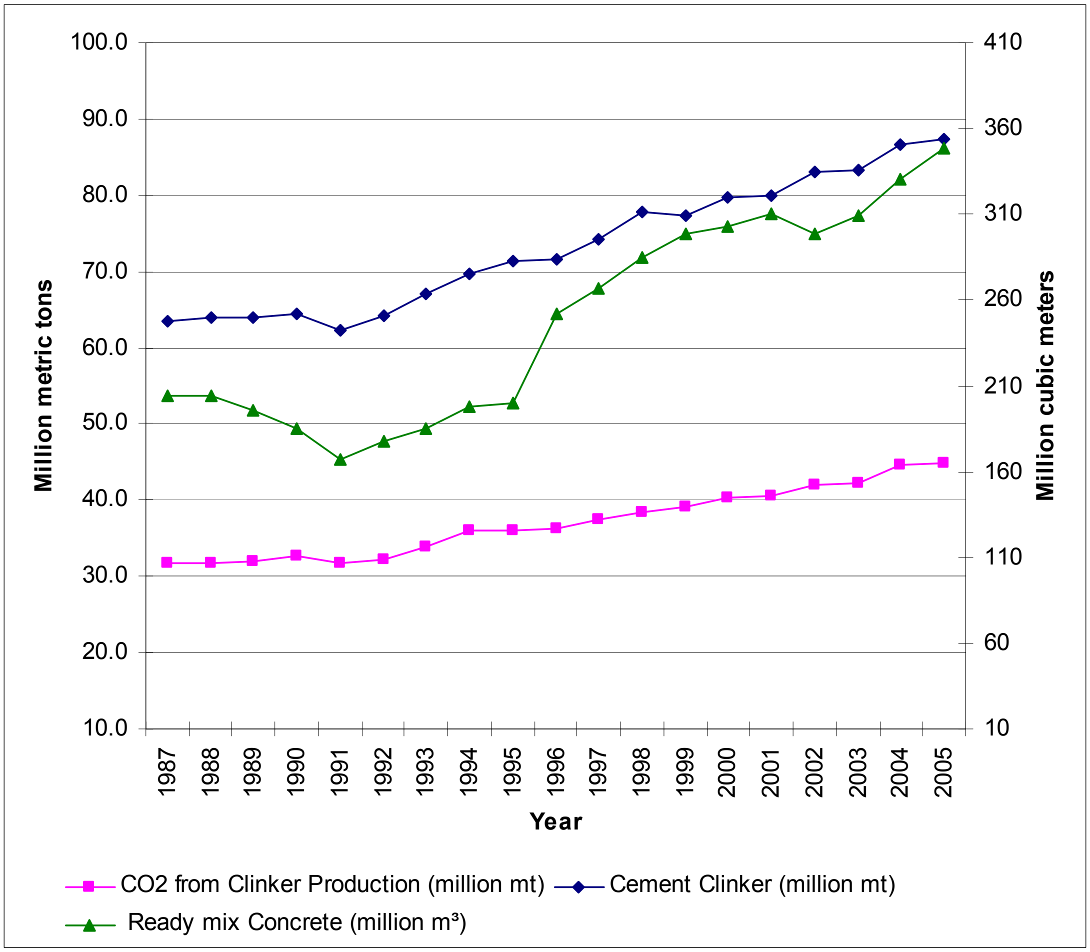

Figure 3. Carbon dioxide emissions from clinker. Clinker and ready mix concrete production shown for comparison of trends. CO_2 data is from Energy Information Administration, 2007. Clinker production from U.S. Bureau of Mines (1987-1993) and U.S. Geological Survey (1994-2005) Cement in Minerals Yearbooks, and ready-mix-concrete production from National Ready Mix Concrete Association, 2006.

The United Nations Framework Convention on Climate Change in Kyoto, Japan (December 1997) set measures that would require developed countries to reduce emissions of greenhouse gases to levels below those of 1990; the U.S. requirement was 7 percent below 1990 levels by 2012. However, emissions in 1997 were 15 percent higher than the 1990 levels (using EIA data). The reductions needed to meet 1990 levels require drastic measures. The cement industry would need to shutdown several older plants, particularly those with wet kiln systems, and or upgrade to more efficient kiln technologies (van Oss, 1998). Switching from coal to less carbon intensive fuels would be another option, and a third option would be to change from the dominance of straight portland cements, reducing the clinker component (currently 95 percent), to blended cements. Changing to blended cements would require modification to existing regulations for building codes to accept blended cements. Limits set on NO_x and SO_x, dioxins, and furans would reduce the ability to use inexpensive waste fuels by requiring more emission control devices.

In 1999, the EPA published the National Emission Standards for Hazardous Air Pollutants (NESHAP) for portland cement. At that time, they applied immediately to new or reconstructed plants, and in June 2002 applied to existing plants. Although this standard was appealed, in June 2002 all portland cement plants were required to comply with the NESHAP for Source Categories for the portland cement industry (PC MACT–maximum achievable control technology). The EPA established a mercury emission limit of 41 micrograms per cubic meter of air for new cement plants, but not for existing plants. Emission limits for total hydrocarbon emissions were set as well. Member companies of the Portland Cement Association agreed in 2001 to a voluntary goal of reducing their average CO_2 emissions (calculated per ton of cementitious product) to 10 percent below 1990 levels by 2020 (van Oss, 2001). The ASTM standard for portland cement was amended in 2004 to allow for up to 5 percent ground limestone in the finished cement. By changing the standard to allow limestone additions there is a proportionate increase in the plant's cement output without increasing CO_2 emissions (van Oss, 2005). A similar change in the American Association of State Highway and Transportation Officials standard needs to occur to have widespread acceptance in the industry (van Oss, 2005).

In September 2003, U.S. cement plants using hazardous wastes as either fuel or raw material were required to comply with the EPA's National Emission Standards for Hazardous Air Pollutants (NESHAP) from Hazardous Waste Combustors (HW MACT; van Oss, 2003). These requirements are part of implementing the Clean Air Act Amendments.

Another way to reduce the CO_2 emissions from clinker production is the use of alternative CaO sources as feedstock. The CemStar^{sm} process patented by Texas Industries (TXI) uses steel slag as substitute for part of the kiln feed (van Oss, 1998). The chemical composition of steel slag is very close to clinker. Slag melts at a relatively low temperature melting point and reacts exothermically, lowering the fuel consumption of the kiln. TXI first tested the CemStar^{sm} process in 1994 using slag from their Chaparral Steel plant in Texas. Other companies including Holcim, Ash Grove Cement, and Rio Grande Portland Cement have acquired licensing for this technology. Annual consumption of air-cooled slag by the CemStar^{sm} process rose from 160 thousand tons in 1995 to 340 thousand tons in 2002 (Yates, Perkins, and Sankaranarayanan, 2003). Benefits of this process include lower CO_2 emissions and use of a byproduct of the iron and steel industry, formerly stockpiled as waste thus reducing fuel consumption per unit of clinker. CemStar^{sm} claims a reduction of energy by as much as 12 percent, lowering of CO_2 by 7 percent and NO_x emissions by as much as 40 percent per ton of clinker depending on the kiln process (Yates, Perkins, and Sankaranarayanan, 2003) with a 10 percent increase in clinker production.

SUSTAINABLE DEVELOPMENT

A primary function of sustainable development is conservation of natural resources for future generations. The cement industry is based on mining of calcareous (limestone), argillaceous (shale), and siliceous and iron-bearing materials to produce clinker. In 2005, 146 Mt of nonfuel raw materials were directly or indirectly mined annually for cement manufacture (van Oss, 2005). This mining has environmental impacts as well. Cement manufacturing also depends on organic non-renewable fuels for calcining materials to clinker. Conservation of these natural resources has added to the desirability of using artificial pozzolans and SCMs. Natural pozzolans require mining of natural resources, and energy for drying, grinding, and in some cases calcining, which creates additional CO_2 emissions making them a less attractive substitute for portland cement..

Adding artificial pozzolans and SCMs to concrete also reduces energy consumption and CO_2 emissions substituting for portland cement. Recycling of artificial pozzolans that are byproducts of industrial processes means fewer waste products going into landfills. With the exception of silica fume, the cost of these materials is less than portland cement.

The durability of concrete is a sustainable attribute in itself because it will not rot, burn, or rust and requires less energy over time to repair or replace (Portland Cement Association, 2007a). The introduction of artificial pozzolans increases the durability of concrete by controlling alkali silica reaction, reducing the permeability, and resisting chemical attack.

TRENDS AND BARRIERS

Pozzolans, particularly fly ash, GGBFS, and silica fume, are on average used in at least 60 percent of ready mix concrete (Portland Cement Association, 2007b). The ready-mix-concrete industry consumes 75 percent of the cement shipped in the U.S. (National Ready Mix Concrete, 2006) and represents a major part of the concrete produced in the U.S. Use of mineral admixtures has been adopted by most state departments of transportation (DOT) and they have specific guidelines for pozzolan use in concrete. The American Concrete Pavement Association maintains a database of state DOT concrete pavement practices on their website (American Concrete Pavement Association, 2007) listing the specifications for fly ash, GGBFS, silica flume, and blended cements for each state in the U.S. and several Canadian provinces. The Energy and Environmental Research Center, a principal agency for research in coal combustion products (CCPs), in 2005 outlined state DOT specifications for disposal and utilization of CCPs (Docker and Jagiella, 2005). The study noted that all states had specifications pertaining to CCPs and most had added specifications for GGBFS as a mineral admixture to concrete since a previous study done in 1992. Many states also have silica fume specifications that are often part of a mixture containing fly ash and GGBFS as mineral admixtures for concrete. Blended cements specifications have been added by many states since the previous survey, an indication of increased use of fly ash and GGBFS by the cement industry (Docker and Jagiella, 2005).

There are barriers to using artificial pozzolans. Some of these barriers arise from lack of data or knowledge on how to use these products. Other obstacles deal with conditions that occurred in the past, such as inconsistency in the pozzolan quality or supply problems that are still cited as concerns in the concrete or cement industry. Terminology can be a barrier; the EPA's classification of fly ash as a non-hazardous material placed it in the category of solid wastes under Subtitle D, which assigns regulation of this material to the states. Each state tends to deal with this classification differently, including how fly ash can be reused.

Other barriers involve changes in environmental regulations that potentially will affect the quality of the product. As an example, the quality of fly ash could be impacted by further regulations on the power generating industry. The lowering of NO_x emissions by low NO_x burners can increase unburned carbon, making the fly ash unsuitable for use in concrete. Some low NO_x systems also leave residual ammonia on the fly ash that could cause ammonia fumes to be liberated from the concrete mix, creating potential respiratory problems for workers (U.S. Environmental Protection Agency, 2003). Silica fume is amorphous and very fine-grained so it must be treated as any other respirable dust with crystalline silica present but below measurable limits.

SUMMARY

Governmental regulations have played a large role in increasing the use of artificial pozzolans and SCMs over the past 25 years. Concerns about energy conservation, emissions, recycling, and conservation of natural resources have motivated this trend. However, without the beneficial properties these materials impart to cement or concrete along with their environmental benefits, these materials would not have become as well accepted in the concrete and cement industries. There are still barriers to use because of differences in state regulations and past experiences with inconsistent quality and availability. Environmental regulations in particular might affect the quality or quantity of some of these mineral admixtures in the future.

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Next Generation Aggregates

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ABSTRACT

Most aggregates are performing the same function they have done for centuries. Our aspirations for aggregates are low – it is enough that they should be cheap, resilient and either pack together well, or stick to cement paste or bitumen. Perhaps we should ask more of them. What could aggregates for the future be, and what could they do?

For materials to perform better in bonded applications, cheap surface modification of aggregates needs to be explored e.g. by sand blasting, surfactant and detergent treatment, and surface coatings. The effects on both natural and waste materials should to be evaluated. The aggregate geologist needs to think of their materials as a series of shapes and surfaces on which many things can be done.

In the area of synthetic aggregates numerous projects have already been undertaken involving fused materials, carbonation and pelletised fines to create usable, conventional aggregate pieces. These studies however need to be expanded to explore the performance of new shapes and microstructures for high quality applications rather than focus purely on the potential use of waste raw materials.

In real life aggregate surfaces are not clean and the potential for bio-aggregate materials and structures is an exciting area to investigate. Reactive surface coatings applied to aggregates also has enormous potential. In order to continue and expand the use of recycled and waste materials we need to take less promising materials and see how they perform in combination with each other, and primary aggregates. The properties of these hybrid mixtures will be surprising and the scientific understanding needs developing. Techniques to model the packing and performance characteristics of these materials and mixtures also need to be explored.

The market will ultimately decide if any of these ideas has ‘mileage’ but we need to be thinking the unthinkable to move on from such a ‘low aspiration’ for aggregate materials! We need a bit more materials science with our geology!

INTRODUCTION

Aggregates today are essentially the same as, and perform the same function as, those used a century ago. We have fine-tuned gradings for improved asphalt and concrete products, developed new mix formulations, and have been effective in scaling up production and processing equipment. Overall we have improved energy efficiency, and reduced some material wastage rates. At the lower end of the market we have increasingly sought to incorporate construction waste materials such as brick & concrete, demolition rubble, asphalt, and industrial wastes such as pfa, slags and china clay sands. Increasingly recycled materials such as crushed glasses are also used in construction materials. Recent research in the UK & Europe has focused on the use of quarry fines, fused materials, plastics and other wastes streams in construction.

Essentially however we still overwhelmingly use crushed rock or naturally particulate materials, in their raw form and use them as drystone or to make a variety of asphalt or concrete mixtures. Aggregates ‘do’ as they ‘did’ in the 1800’s. What is needed is a fundamental look at the potential for new advanced aggregate products that engineers and architects can use in improved infrastructure designs. This is not to replace the bulk stone market but to get added value from these essential non-renewable resources. From a financial viewpoint it is well known that aggregates are the cheapest of the components in most bound structures. They therefore have an important role in reducing costs by allowing the lowest possible proportion of the expensive binder components. In typical concretes, for example, the aggregates occupy around 70-80% of the volume but only 30% of the cost. The cement by contrast occupies only around 10-15% by volume and 30% by cost. Any savings the aggregate can make in the binder needs are therefore highly efficient in overall cost terms.

This could be termed the a plea for a future advanced aggregates market but the potential approaches discussed below also address the things we do or could do with our current aggregate products.

SHAPE & MICROSTRUCTURE CHARACTERISATION AND MODIFICATION

Aggregates characterisation and testing usually involves assessing the gradings and relevant physical properties. Natural sand & gravel particle size distributions are crucial to determining performance and use in different products. Most geologists and technologists in construction materials field will testify to how important aggregate and sand shape can be in asphalt and concrete applications but we rarely seriously attempt a rigorous quantification of this. Gravels and crushed aggregates are usually only described in terms of their shape by means of simple max to min length ratio or similar tests that define their flakiness. Sands are just described in subjective terms. This means that we have only anecdotal evidence over what role shape plays in performance and very limited information on what aspects of shape may control these perceived differences.

New video and laser based imaging systems can now rapidly and simultaneous analyse size and shape of an aggregate sample giving for the first time a quantified particle size distribution and shape parameter information. These are currently being used in research to assess the most important parameters to describe shape and how these impact on product performance. They also have the potential to make sieve analysis a thing of the past.

Samples are currently being run to assess performance in a wide range of aggregate applications against the potentially measurable shape parameters. This opens up a whole new area of product improvement based on tailoring shape to reduce cement and binder demand, improve placement, drainage and durability.

Microstructure characterisation is also a technology that is under used. Non-destructive 3d visualization using high energy x-ray CT- scanning to reveal microstructure, and high resolution surface imaging are all available and have major applications in assessing the role and potential for modification of microstructure in aggregate performance. The ability to use the microstructure in holding active additives or simply keying in of binding agents is still rarely considered. The mechanical performance of different types of aggregates particularly in wearing applications also still needs explanation, and in many cases microstructure will be part of the story.

SURFACE ACTIVE AND MODIFIED AGGREGATES

Considered objectively aggregates are really engineering shapes with surfaces on which we hope certain things will or will not happen. We desire aggregates with generally low surface area to volume ratios and hope that bitumen and cement paste will stick effectively to their surfaces. The majority of the aggregate grain simply occupies space, it is the surfaces on which the majority of the 'complicated stuff' must take place.

It is therefore surprising that so little is done to optimise the surface properties of aggregates. We know that some aggregates are prone to 'stripping' as a result of poor bitumen adhesion to grain surfaces. The oil reservoir and mineral processing specialists are very familiar with the concepts of hydrophobic or hydrophilic surfaces on minerals and rocks. The quarrying industry crushes the same rock or takes the same sand, and sends it to the concrete plant where a hydrophilic surface is required to adhere well to water based cement pastes, and the asphalt plant where it must by contrast be oleophillic (hydrophobic) in order to adhere well to bitumen. Is it any surprise that we sometimes get caught out? The bitumen companies are of course happy to sell expensive surface active additives as miracle cures when problems occur.

There is a whole science of surface modification than can be applied to aggregates to give improved product performance at minimal cost. The industrial minerals industry has much experience of coating carbonates and kaolins, but low cost approaches for aggregates are now being explored. These will be most effective where the aggregates are near critical specification boundaries thus justifying the additional costs but simple approaches may be of benefit elsewhere. Surfaces can be modified by simple or more complex processes such as sand blasting, surfactant and detergent treatment, surface coating, rapid acid leaching, impregnation, flash heating, and even laser spalling. These have interesting and variable effects on both natural and waste materials. What is needed is the development of these approaches using cheap equipment and chemicals (probably wastes) to allow low cost technologies to be deployed. A series of trials on some of these techniques are being started.

SYNTHETIC AGGREGATES

The use of quarry fines and other fine-grained industrial wastes has received considerable attention over recent years with a view to attempting maximum utilisation of the material recovered from crushed rock aggregate sources and sand & gravel deposits. Fines have been used to make synthetic aggregates using pelletisation, resin or lime binders, and have also been fused or calcined in an approach similar to lightweight expanded aggregate production. Although showing promise these generally produce a reasonable aggregate but at high cost that would have difficulty competing with conventional primary aggregates even with the primary aggregate tax (Aggregate Levy) applied in the UK.

These synthetic aggregate studies have however generally sought to replicate standard aggregates with inevitable cost disadvantages. Once you have the 'freedom' to reconstruct an aggregate from a powder or waste material you have the ability to tailor its shape and microstructure to create high performance rather than typical aggregate materials. This would seem to make more economic sense.

Work has also been started on using these materials to make designed or exotically shaped materials, with bespoke surfaces and microstructures that can be used in specialist applications with significant improvements in performance and savings in whole product costs.

Non-destructive 3d visualization using high energy x-ray CT- scanning to reveal microstructure, and high resolution surface imaging are all available and have major applications in both this and natural aggregate product characterisation. Such synthetic products are also being looked at elsewhere in Europe and are already entering the market in some cases.

While it is unlikely that the economics of stone cutting would permit industrial deployment, water jet and related techniques can be used to create complexly shaped aggregates. More importantly new comminution technology using microwave and ultrasonic assisted crushing will allow newly shaped aggregates to be formed from solid rock. The technology is being developed mainly for large scale metal mining companies to process low grade ores efficiently but the technology will soon trickle down to the aggregate industry.

HYBRID MATERIALS

The use of waste materials from construction and industrial processes in aggregate applications is now widespread. The re-incorporation of asphalt, crushed brick and concrete has now been well refined. The utilisation of such materials is considered by many in the industry to be nearing saturation. To use any of the less obvious waste materials will probably require them to be incorporated in mixtures with better quality aggregates.

The performance of such complex mixtures is largely unknown and unresearched. The technology of hybrid materials incorporating natural aggregates, multiple wastes or secondary materials and novel binders is an area that requires significant investigation. Such hybrid materials involve complex particle shapes (consider crushed bricks with perforations), and a range of strengths, surface properties, porosities, and gradings. These materials will unlock the second generation of waste incorporation into aggregates and will also throw up surprises as to what potential cost and performance benefits can be gained from such hybrid mixtures.

AGGREGATE STRUCTURE MODELLING

Aggregates are often used as graded products in structures due to their ability to pack well. The packing is strongly controlled by gradation, and maximum packing density grading curves are widely used. The technology for characterising and quantifying shape however also opens up the possibility of using shape parameters in modelling of products based on the complexity of real aggregate shapes as opposed to theoretical approximations.

Visualisation software allowing packing parameters for complex shapes is under development in mathematical modelling applications, and will allow optimisation for today’s products. It will also allow the potential of more complex shapes top be assessed and modelled and there are certain to be surprises as to what topological properties complex mixtures of natural and waste products can generate. This type pf modelling is already underway for cement mixtures, examining packing and pumpability in particular.

REACTIVE AGGREGATES

Most aggregates are used as cheap, inert, space filling, structurally competent extenders that minimise binder requirements or pack well unbound. This is again a rather limited aspiration for our geological materials. The surfaces of the aggregates can, instead of being surfaces purely to adhere to, be templates and substrates on which reactions can occur. In a simple sense we can use them to promote the binding reactions. Reactive surface coatings could be applied to aid the bonding between binder and aggregate. Powder, vapour or solvent coating technology is ubiquitous and could easily be applied to aggregates.

We could also take the process further by using aggregate surfaces to scavenge unwanted environmental contaminants, coat some grains with a binder others with a hardener so delaying hardening or perhaps the reverse. This could allow new forms of placing and structures to be developed in collaboration with construction engineers, as well as achieving strengths and stabilities well in excess of normal products.

BIO-AGGREGATE STRUCTURES

In the real world aggregate surfaces are not clean and fresh. Biological activity starts on broken rock surfaces within days, and bacteria are capable of both mineral breakdown and mineral precipitation. Some of these mineral precipitates are highly durable, while others form ‘ductile’ structures where the grains are held loosely in a web of filaments.

There is a complete world of possibilities for developing bio-aggregate structures where aggregates are held in place, or cemented by biological processes without the need for high energy binders. These could simply form structures or have enhanced durability, allow deliberate property changes over time, or again develop the ability to simultaneously remediate contamination as well as form a structure. This is getting more speculative but work is again starting to assess the potential.

SMART AGGREGATES

There is potential to consider that the humble aggregate could be used for doing rather more than just occupy space, it could report on conditions within the structure in which it has been incorporated. An aggregate grain might be able to reveal when it is strained beyond a certain point, or when it is ineffectively bound to those around it. This could mean harnessing properties such as conductivity or Raman shift to reveal the grains performance.

‘Cyberliths’, synthetic aggregate grains capable of sending signals to be monitored outside of the engineering structure, already exist but are expensive and used only in highly specialised cases. Developing aggregate materials that do a similar job cheaply will be a challenge for the future.

THE FUTURE HERE TODAY

In case this all seems rather academic, theoretical and a million miles form the local aggregate quarry it is worth noting some examples of what is already happening. The Italcementi Group has developed photocatalytic concrete incorporating titanium dioxide powder causing the external surfaces of roads and buildings to breakdown nitrogen and sulphur bearing gases and ozone in the urban environment is already in use. Self healing concrete containing fibres of sealant that shear when the concrete cracks allowing the sealant to immediately seal the crack, are also soon to be deployed.

Personally I would like to develop aggregates that change colour as the road freezes thus warning of ice danger or develop a modified type of road construction that acts as a large solar panel! The global construction industry is around $3 trillion per year and around £1 trillion of this is for materials. The opportunities for smarter aggregates are enormous.

CONCLUSIONS

Ultimately the aggregate industry is market driven and any technological developments must create products that can be sold for a profit. The industry is traditionally a rather conservative one with a strong record in ‘product development’ but a poor history of ‘research & development’. In other words the industry needs to be looking somewhat further into the future and seeing what might be possible in the longer term. Some companies are doing this but truly novel ideas take time to be developed and commercialised. The next generation of aggregates starts today.

One Hundred Years of Industrial Mineral Production in 17 Western States

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ABSTRACT

The U.S. Geological Survey annually reports the domestic production of 42 industrial mineral commodities. During 2005, production was reported for 28 industrial minerals in one or more of the 17 western States of Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming. Six other industrial minerals were previously produced in one or more of those states, but production has ceased. In total, more than three quarters of the industrial minerals tracked by the U. S. Geological Survey are, or have been, produced in the western States.

The industrial mineral commodities that are being, or have been, produced in the western states were identified through a review of the U.S. Geological Survey and U.S. Bureau of Mines Minerals Yearbooks from 1906 through 2005. This report addresses seven commodities (diatomite, feldspar, fluorspar, manganese, mica, perlite, and potash) in detail. The years that the seven industrial minerals were produced, and the states in which they were produced, were tallied in a spreadsheet. The data were grouped by commodity and converted to simple bar graphs. A line graph showing U.S. production was placed above the bar graphs. This allows a visual assessment of how, over time, production relates among the western states which, in turn, can help provide insights into the geologic, economic, societal, or environmental factors that influence the start or demise of various industrial mineral operations.

INTRODUCTION

> "The fact that [the *Mineral Resources of the United States*] has been consistent for twenty-five years makes it easy for the student of any industry to obtain a historical grasp of his subject by consulting all the volumes, which are usually accessible in public libraries." (Day and Parker, 1907, p. 9).

Study area and methodology

This paper has been prepared for the *43rd Forum on the Geology of Industrial Minerals*. The theme of the meeting—Then & Now—helped define the scope of this paper, which is a discussion of the past and current production, and occurrences of industrial minerals of significant importance in the western States of Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming. For the purpose of this paper those 17 states are referred to as “western States.”

The U.S. Geological Survey (USGS) and U.S. Bureau of Mines (USBM) have published annual reports on mineral commodities since 1883, reporting on production data as far back as 1872. Many of those commodities can be classified as industrial minerals. Over the years the list of industrial minerals that have been reported by the USGS or USBM has changed as the demand for minerals waxed or waned.

The definition of what constitutes an industrial mineral is somewhat arbitrary. A simple definition of an industrial mineral is given in the American Geological Institute Glossary of Geology (Jackson, 1997, pg. 324): “Any rock, mineral, or other naturally occurring substance of economic value, exclusive of metallic ores, mineral fuels, and gemstones.” Nevertheless, some minerals, especially metallic ores, are classified in various reference books as industrial minerals, especially when they have a significant application for non-metallurgical uses. Examples of such minerals include ilmenite and rutile (titanium), spodumene and lepidolite (lithium), chromite (chromium), and rhodochrosite, rhodonite, and alabandite (manganese).

Given the ambiguity in the definition of an industrial mineral, the USGS currently publishes annual reports on 42 of what can be classified industrial minerals. Of these, 32 are, or have been, produced in the western States (table 1). Common, widespread, naturally occurring construction materials such as sand and gravel, crushed stone, and clay have been mined in all 17 western States. These industrial minerals generally are used with only minor amounts of processing. Other common industrial minerals such as dimension stone, gypsum, industrial sand, salt, talc, and common industrial mineral products (cement and lime), are also produced in many, but not all, of the western States. There is also a significant number of less common industrial minerals produced in western States that have very limited geographic occurrence.

This report addresses seven industrial minerals that have been produced in the western States; diatomite, feldspar, fluorspar, manganese, mica, perlite, and potash. The years that the various industrial minerals were produced, and the western States in which they were produced, were identified through a review of the U.S. Geological Survey and U.S. Bureau of Mines Minerals Yearbooks from 1906 through 2005. The results were recorded in a spreadsheet and the data were grouped by commodity and converted to simple bar graphs. A line graph of the seven commodities, showing total U.S. production, exports, imports, and stockpiles (for selected commodities) was superimposed above the bar graph. Data for the line graphs, obtained from Kelly and Matos (2005), allows a visual assessment of how, over time, production relates among the western states, and how that production relates to the U.S. production. Socioeconomic and geologic aspects affecting the exploitation of those minerals were identified through a review of the USGS and USBM Mineral Resource Yearbooks of the U.S. and the 7 editions of the SME/AIME publication *Industrial Minerals and Rocks*. This information can help provide insights into the geologic, economic, societal, or environmental factors that influenced the industrial minerals industries.

Table 1 – States where industrial minerals currently are being produced (X) or previously have been produced (P). Commodities shown in bold type are discussed in detail in this report.

	AZ	CA	CO	ID	KS	MT	NE	NV	NM	ND	OK	OR	SD	TX	UT	WA	WY
Asbestos	P	P		P		P						P				P	P
Barite	P	P	P	P		P		X	P					P	P	P	
Beryllium	P		P	P					P				P		X		P
Boron minerals		X															
Cement / lime	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X
Clay	X	X	X	P	X	X	X	X	X	X	X	X	X	X	X	X	X
Diatomaceous earth	**P**	**X**		**P**	**P**			**X**	**P**			**X**			**P**	**P**	
Feldspar	**P**	**X**	**P**	**X**				**P**	**P**		**X**		**X**	**P**			**P**
Fluorspar	**P**	**P**	**P**	**P**		**P**		**P**	**P**					**P**	**P**	**P**	**P**
Garnet		P		X		P								P			
Gemstones	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Gypsum	X	X	X	P	X	P		X	X		X	X	X	X	X	P	X
Iodine		P									X						
Lithium minerals /brine	P	P	P					X	P				P				
Magnesium minerals / brine		X						X	P		P			X	X	P	
Manganese compounds	**P**	**P**	**P**	**P**		**P**		**P**	**P**		**P**	**P**	**P**	**P**	**P**	**P**	**P**
Mica	**P**	**P**	**P**	**P**		**P**		**P**	**X**				**X**	**P**	**P**		**P**
Perlite	**X**	**X**	**P**	**X**				**X**	**X**			**X**		**P**	**X**		
Phosphate rock		P		X		P									X		P
Potash		**P**	**P**			**P**	**P**	**P**	**X**		**P**		**P**	**P**	**X**	**P**	**P**
Pumice	X	X	P	X	X	P	P	P	X	P	P	X		P	P	P	P
Rare Earths	P	P	P	P		P											P
Salt	X	X	P	P	X			X	X	P	X			X	X		
Sand & gravel, construction	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Sand, industrial	X	X	X	X			X	X		X	X	P		X	P	X	P
Sodium carbonate, soda ash, trona, nahcolite, sodium sulfate	P	X	X			P		P				P		P	P	P	X
Stone, crushed	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Stone, dimension	X	X	X	X	X	X		P	X		X	P	X	X	X	X	P
Talc / steatite / soapstone		X				X		P	P			X		X		P	P
Titanium minerals		P		P													
Tripoli		P		P							X			P			
Vermiculite			P			P		P						P	P		P
Zeolites	X	X		X				X	X			P		X			X

REVIEWS OF SELECTED INDUSTRIAL MINERALS

Diatomite

> "As with many other nonmetallic mineral markets for diatomite are changing constantly; certain new uses are being developed while others are being abandoned." (Hatmaker and Davis, 1932, pg. 160).

The ability of the diatomite industry to adapt to changes in market demand is the hallmark of the industry.

Diatomite (known as "infusorial earth" prior to 1914) was first discovered in North America in 1839 near West Point, New York, and small amounts of diatomite were mined and used as an abrasive, absorbent, and filler in the eastern United States as early as 1850 (figs. 1 and 2). Alfred Nobel's invention of dynamite in 1867 created a major market for diatomite, which was used as an absorbent and stabilizer for nitroglycerine. In 1900, the first U.S. patent was issued for the use of diatomite in beer filtration, which remains as one of diatomite's primary modern applications (Dolley, 2002).

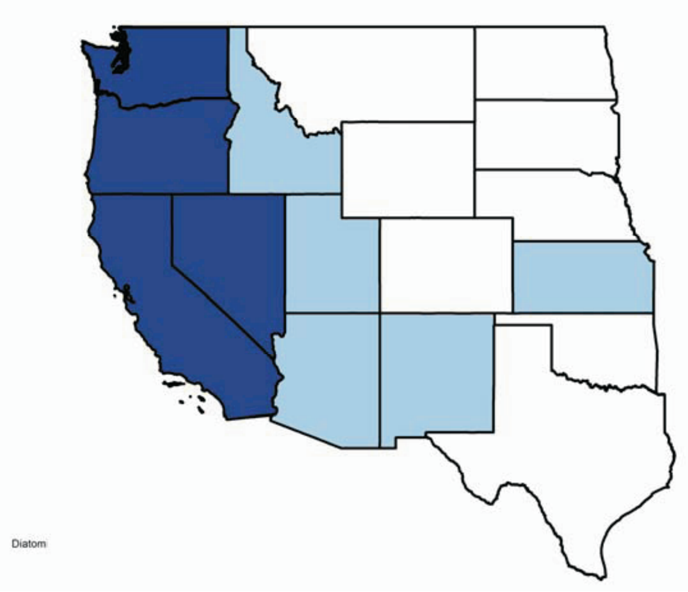

Figure 1. Western States where diatomite was produced in 2004 (dark blue), or previously has been produced (light blue).

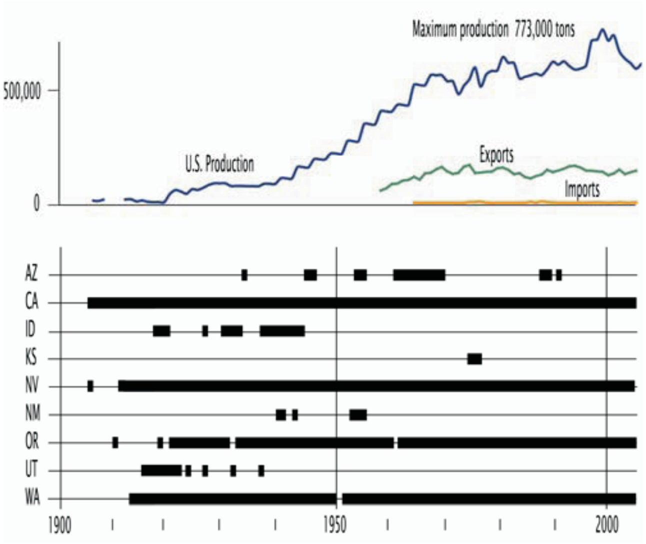

Figure 2. Bar graph showing periods of diatomite production in western States, and line graph showing U.S. production, exports, and imports, from 1905-2004.

The fledgling U.S. diatomite industry expanded in about 1900 with the exploitation of the deposit at Lompoc, California. The western States have dominated domestic diatomite production ever since. The industry has been developed by large individual companies or by trade organizations, and has been characterized by a high degree of efficiency in developing markets (Cummins and Mulryan, 1937). Some uses, such as a filler in records for "talking machines" (Phalen, 1911a) come and go. However, uses such as filtration and insulation provided long-term, growing markets. During the 1920s, the development of new processing techniques, including calcination, and grade and sizing technologies, enabled diatomite to be tailored to a variety of market applications and end uses (Dolley, 2002). Even during the depression of the late 1920s and early 1930s, the fillers, filtration, and sugar refining industries buoyed the market. The period during World War II saw great advances in the applications of diatomite for filtration of electroplating solutions, cutting oil emulsions, and biological applications such as penicillin and streptomycin. Diatomite was also used as a filler in camouflage paint, insecticides, and paper, and as litter for poultry and animals (Cummins and Mulryan, 1949).

In the U.S., diatomite production is concentrated in California, Nevada, Oregon, and Washington. Five other western States have had relatively short term forays into the industry. While all commercial diatomite operations in the United States are in western States, many of the markets are in eastern States. Consequently, transportation charges are a significant portion of the delivered cost of diatomite to eastern markets.

Today, filtration of products such as beer, liquors, and wine, and the cleansing of greases and oils, continues to be the leading use for diatomite. In addition to many historical uses such as abrasives, thermal insulation, and fertilizer carrier, new uses include the removal of microbial contaminants (bacteria, protozoa, and viruses) from public water supplies, the filtration of human blood plasma, and filler in plastic film. Emerging applications for diatomite include pharmaceutical processing and use as insecticides that are nontoxic to humans (Founie, 2006: Breese, 1994).

During the past 100 years the diatomite industry has grown consistently due to the diversification of its markets. Challenges to U.S. exports to Europe, the Far East, and Latin America began during the 1980s (Kadey, 1983a). In spite of that competition, during 2005 the United States exported diatomite to 97 countries. California and Nevada are the top two producing states, and together produce 70 percent of the U.S. diatomite production. The United States is the world's leading producer of diatomite (Harben, 2002). China is the main production competitor of the United States (Founie, 2006).

Feldspar

> "Commercially, feldspar is obtained only from pegmatites. According to Hess 'The pegmatites are undoubtedly the most bizarre, the most contradictory, the most complex and altogether the most interesting group of rocks known.' " (Burgess, 1937, pg 261).

Likewise, feldspar is one of the most bizarre, contradictory, complex, and interesting group of industrial minerals, and serves as a prime example of the ties between industry and outside influences that control its fate.

Feldspar production in the U.S. dates back to the 1860s following the establishment of the pottery industry (figs. 3 and 4). In 1900, feldspar was produced by selective mining and hand sorting of coarse-grained pegmatites from deposits located in Connecticut, Maine, New York, and Pennsylvania (Potter, 2002). At the time, most feldspar was ground by the user, but by 1919 there were grinding mills in New Jersey, New England States, and Ohio, all supplied with hand-cobbed feldspar from New England.

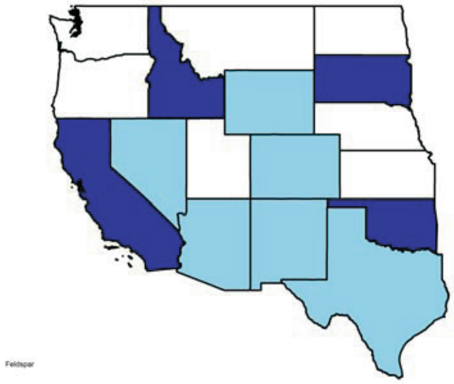

Figure 3. Western States where feldspar was produced in 2004 (dark blue), or previously has been produced (light blue).

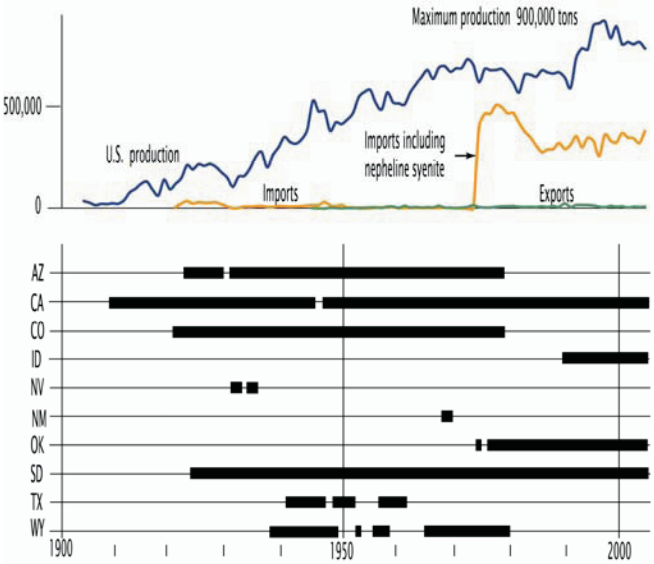

Figure 4. Bar graph showing periods of feldspar production in western States, and line graph showing U.S. production, exports, and imports, from 1905-2004.

A small feldspar industry began in the western States near Chualar, in Monterey County, California, where, during 1910, several hundred tons of feldspar were produced (Bastin, 1911). In the northeast, the weather during New England winters interrupted feldspar supplies. In response, deposits were developed in the Spruce Pine area of North Carolina during the 1920s. About the same time, development of feldspars around Denver, Colorado, and Black Hills of South Dakota, and the construction of a mill in Denver, boosted western State feldspar production.

During 1941, there was a record production of glass containers. At that time North Carolina led the production of crude feldspar, followed by South Dakota and Colorado; while Colorado led the production of ground feldspar, followed by South Dakota, Tennessee, New Hampshire, and North Carolina (Metcalf, 1943). Since then North Carolina consistently led in combined crude and ground feldspar production (regularly producing over 40 percent of U.S. production), with a few western States regularly showing up among the top six producers.

The flotation process enabled treatment of ores in which feldspar was more intermixed with quartz, mica, and other accessory minerals. The first commercial flotation plant began operation in North Carolina in 1946 (Potter, 2002).

Nepheline syenite is a feldspathic rock that can be used as a substitute for feldspar in fillers, glass, and pottery. The USBM began recording U.S. imports of nepheline syenite in 1939, when about 26,500 tons were imported from mines in Ontario, Canada (Potter, 2002).

While the states battled for production supremacy, the industry battled the economy. The history of the feldspar industry is typified by a cyclic nature brought on by its dependence on the glass and building industries. For example, during the Great Depression the value of building contracts awarded in 1932 decreased nearly 56 percent from 1931. Feldspar production decreased 29 percent for the same period, and was 50 percent less than in 1928 (Rogers and Galiher, 1933). In 1940, only eight years later, a substantial rebound in residential building combined with a new record high in glass-container output resulted in record feldspar production (Metcalf, 1941).

The feldspar industry is also characterized by shortages followed by construction of new facilities, which has resulted from time to time in oversupply and depressed prices. For example, the overcapacity and low prices in the 1930s described above were followed by shortages, increased imports, and higher prices in the 1940s and 1950s (Rogers and others, 1983). The process repeated itself a number of times in the latter half of the 20th century.

Periods of shortages stimulated increased milling capacity, and the modern equipment of newer mills allowed producers to make inroads into markets historically dominated by older companies (Metcalf, 1941). Other factors affecting success of feldspar businesses include quality and uniformity of product including efficiency in production, estimation of reserves; exhaustion of reserves; transportation costs; and business practices including effectiveness of market studies, estimating start-up expenses, miners' wages, and availability of capital to maintain and modernize operations (Burgess, 1937; Castle and Gillson, 1960; Rogers and others, 1983.)

During the past 100 years some feldspar businesses thrived while others failed; both the result of the combined influence of many economic, geologic, and social factors. Recent influences include product substitution, recycling of glass, land use controversy (NIMBY), and environmental issues including air and water pollution. Nevertheless, the feldspar industry remains mature and highly competitive (Kauffman and Van Dyk, 1994). The U.S. is largely self sufficient in feldspar production, and only imports about 2 percent of its raw feldspar demand from Mexico and Turkey.

Fluorspar

> "The [fluorspar] deposits thus far exploited are, however, confined to five States—Arizona, Colorado, Illinois, Kentucky, and Tennessee. … The great size and purity of the fluorspar deposits of the Illinois-Kentucky district indicate that for many years they will continue the main source of domestic production" (Buchard, 1907, pg. 1063).

Fluorspar is the commercial name for fluorite (calcium fluoride), the principal source of fluorine. Production of small amounts of fluorspar began in Colorado in the early 1870s when it was used as flux in smelting gold and silver (Davis, 1923). During the late 1800s fluorspar was used primarily in the preparation of hydrofluoric acid, in the manufacture of opalescent glass, and as a flux for iron smelting. The use of fluorspar in iron smelting was small during this period because it had a higher price than limestone and usually was more distant from iron-making centers. Advantages of fluorspar over limestone as flux in basic open-hearth steel plants became known about 1899, thus increasing demand. Production in Colorado increased in 1903 when the basic open-hearth steel furnace opened in Pueblo, Colorado. Fluorspar from New Mexico was shipped to the steel mill at Pueblo, Colorado, beginning in 1909. Production of fluorspar throughout the country fell during the early 1930s (figs. 5 and 6). In addition, the development of fluorspar mined from shallow workings in Kentucky resulted in dramatic price reductions (Davis, 1933). A noteworthy feature of the industry is that during the depression many fluorspar companies kept their mines and mills operating to maintain a workforce even though demand did not justify it (Davis, 1932).

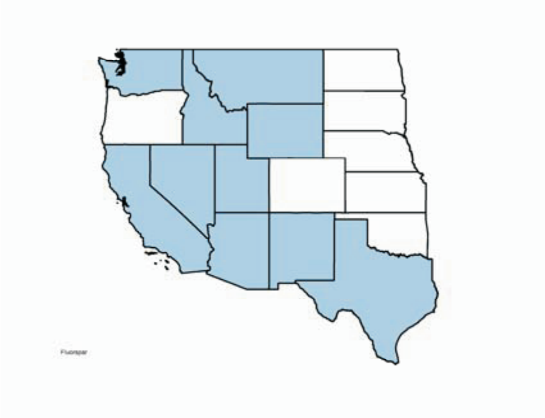

Figure 5. Western States where fluorspar previously has been produced.

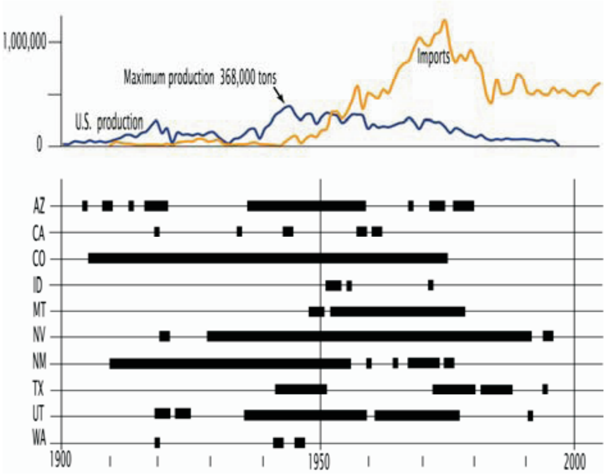

Figure 6. Bar graph showing periods of fluorspar production in western States, and line graph showing U.S. production, exports, and imports, from 1905-2004.

Following the Great Depression the use of fluorspar was stimulated by a resurgence of the steel, aluminum, chemical, and ceramic industries. Record domestic production of fluorite occurred during 1943. Illinois was the primary producing State, although Colorado and New Mexico established record shipments (Davis, 1945). Overall, domestic production gradually declined after 1943, and increases in demand were largely met from foreign imports. Following World War II, the use of anhydrous hydrogen fluoride (HF) as a catalyst in the manufacture of alkylate for high-octane fuel, and the advent of chlorofluorocarbon (CFC) increased demand (Fulton and Miller, 2006). During 1974, demand for fluorspar peaked; 88 percent of the demand was supplied from imports, most from Mexico (Wood, 1976). Fluorspar production in western States dropped significantly during the 1950s because of strong competition from foreign sources. During the last quarter of the 20th century, fluorspar's use in steelmaking decreased dramatically. During the 1970s, fluorspar production ceased in most western States. In 1987 the Montréal Protocol was adopted to phase out production of CFC. The last fluorspar mine in the U.S. ceased production in 1996.

Today about 87 percent of reported fluorspar consumption goes into the production of hydrofluoric acid (HF) and aluminum fluoride. HF is the primary feedstock for the manufacture of virtually all organic and inorganic fluorine-bearing chemicals and is also a key ingredient in the processing of aluminum and uranium. The remaining fluorspar was used as a flux in steelmaking, in iron and steel foundries, primary aluminum production, glass manufacture, enamels, welding rod coatings, cement production, and other uses or products (Miller, 2006).

The United States imports 100 percent of the fluorspar it uses from China, South Africa, and Mexico (McCartan and others, 2006).

Manganese

> "[I]t is probably true that the industries of any nation are most stable when it contains within its borders the basic raw materials essential to its industries, but it is apparent that modern industries in many larger nations demand a diversity of raw materials rarely available on one continent." (Hewett, 1917, pg. 29-30.)

Manganese plays a critical role in the production of steel. Although manganese deposits occur in the United States, their inferior quality has left the industry vulnerable to foreign competition. Early in the 20th century the U.S. Government took steps to ensure adequate supplies of manganese ore in case of emergencies (Corathers and Machamer, 2006). Many of the best sources of manganese in the United States, albeit inferior to foreign sources, occur in the western States (figs. 7 and 8). Consequently, the government projects, and the fate of the steel industry, strongly influenced the development of manganese resources in the west.

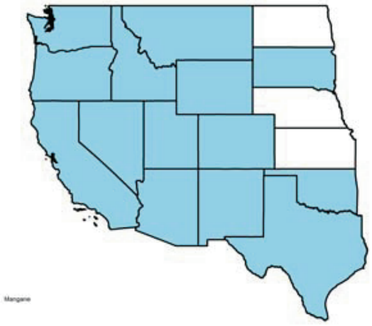

Figure 7. Western States where manganese previously has been produced (light blue).

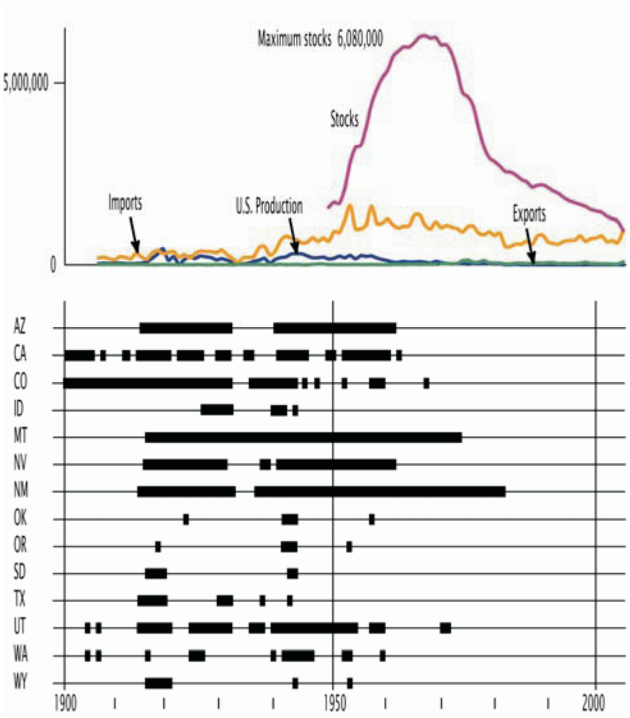

Figure 8. Bar graph showing periods of manganese production in western States, and line graph showing U.S. production, exports, imports, and stockpiles, from 1905-2004.

The use of manganese in steel dates from 1839 when it was shown to improve malleability of ferrous articles (Corathers and Machamer, 2006). The late 19th century manganese industry of the United States was poorly developed. Only a few manganese mines operated in a business-like fashion, and the bulk of manganese came from small workings "that were operated irregularly and inefficiently by individuals with little technical ability and less capital" (Eckel, 1907, pg. 103). Before World War I, annual domestic ore consumption of manganese was about 100,000 tons, of which approximately 90 percent was derived from imported ore (Jones, 2002). Even though requirements for manganese increased during World War I, transport of ore from foreign sources was seriously menaced and domestic production grew. Prices declined following the signing of the armistice, but rose again with the imposition of the Tariff of 1922, which imposed a duty of 1 cent per pound of contained manganese on foreign ores containing greater than 30 percent manganese (Ridgway, 1932).

But the average grade of domestic ore was not a high as foreign ore, and by 1925, competition from foreign sources again caused a decline in domestic prices. In 1927, a new process involving sintering of rhodochrosite ore of the Butte district was developed, and various tariffs were imposed to allow new treatment processes to be put into effect (Ridgway, 1932).

During the Great Depression, steel production was lower than any year since 1901, and during 1932 steel plants operated at only 19 percent capacity, causing a major downturn in domestic manganese production. In June, 1939, President F.D. Roosevelt signed the Strategic Materials Act authorizing the purchase of strategic materials for stockpiling. That act gave a major boost to the manganese industry (Ridgway and others, 1941). One of the largest contracts was with Anaconda Copper Mining Co., Butte, Montana that supplied 80,000 long tons of nodulized rhodochrosite ore containing at least 55 percent manganese annually for 3 years (Ridgway and others, 1941).

The demand for war materials increased steel production during WWII. After the war, metallurgical advances required the manganese industry to provide higher grade ore with lower impurity content for use in steel (Jacoby, 1983).

During 1950, the rate of manganese imports was believed to be about the maximum that could be obtained under existing conditions, and the need for developing new deposits and sources of manganese, foreign and domestic, became pressing. The Defense Production Act of 1950 provided government assistance in developing domestic minerals. The first contract to be written (1950) was for production of high grade sintered manganese concentrates from Clark County, Nevada (Melcher, 1953). A report to President Truman by The President's Materials Policy Commission (1952) recommended that the United States should continue to rely on imports for peacetime supplies of manganese, and that the principal concern was to ensure against wartime shortages. During 1960, Nevada, with Government purchases under special contract, provided more than half of the domestic production of manganese ore containing 35 percent or more manganese (DeHuff and Fratta, 1961).

The end of the Cold War and declines in domestic steel production diminished the need to maintain stockpiles (Corathers and Machamer, 2006). Domestic production virtually ceased by 1970, and manganese began to be sold from those stockpiles (DeHuff, 1980). In 1970, the Director of the Office of Emergency Preparedness concluded that manganese was not being imported into the United States in such quantities or under such circumstances as to threaten to impair the national security. The nation's only mine producing manganese ore, concentrate, or nodules greater than 35 percent manganese ceased its operations in New Mexico that same year (DeHuff, 1972). Ferruginous manganese ores containing 10 percent to 35 percent manganese continued to be produced and shipped from New Mexico until 1981.

Today the U.S. imports 100 percent of the manganese it consumes, primarily from Gabon, South Africa, Australia, and Brazil. Over the past 100 years the perception of the importance of manganese to the U.S. economy and security has varied. During some periods the exploration and development of domestic manganese resources was encouraged by government programs and protected by tariffs; during other times the supply was left to imports.

Mica

> "Domestic reserves doubtless are adequate to produce on an increased scale, but not in open competition" (Spence, 1937, pg 463.)

The high cost of hand-processing, classifying, trimming, and splitting mica, especially sheet mica, has created a great disadvantage for domestic production and exploration in trying to compete with low-cost producing foreign countries. Although domestic sources of mica are numerous, large size material does not occur in the United States in substantial quantities.

Mica production in the United States began in 1805 in New Hampshire (Chapman, 1983). The U.S. originally outpaced other countries in mica production because of its reliance on stoves with mica "windows" rather than open fireplaces (Tanner, 1994). In the early days of electric power generation, sheet mica was the only material available with electrical and mechanical properties suitable to operate at the temperatures necessary for the efficient functioning of the electrical equipment. The electrical industry began to grow in the late 1870s, creating many new applications and tremendous demand for mica. The tendency in the industry was to work all mica mines only for present values, with little regard for future production (Sterrett, 1907), and the electrical industry grew so fast that domestic reserves were rapidly depleted. During 1884, imports began to affect the U.S. mica industry, and by 1885 India had become a major supplier of sheet mica. Tariffs were imposed on mica imports in 1890 to protect U.S. producers (Tanner, 1994).

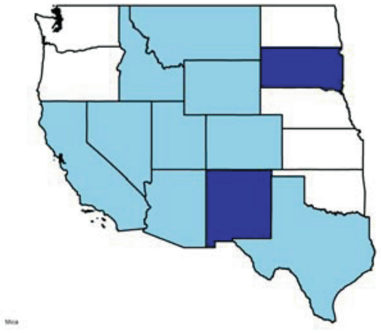

Figure 9. Western States where mica was produced in 2004 (dark blue), or previously has been produced (light blue).

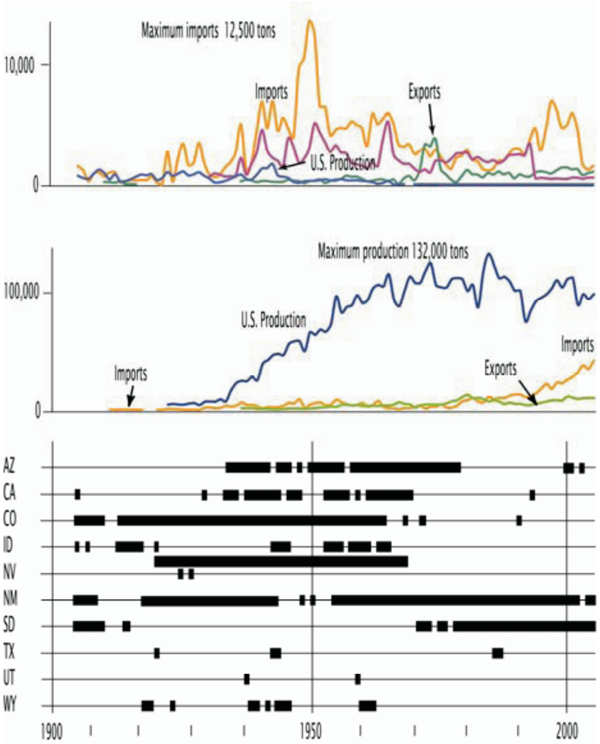

Figure 10. Bar graph showing periods of sheet mica and flake mica production in western States, and line graph showing U.S. production, exports, imports, and stockpiles (red) of sheet mica (upper line graph), and U.S. production, exports, and imports of flake mica (lower line graph) from 1905-2004.

A patent was issued in 1892 for built-up mica whereby flakes of mica were bound together in a way that maintained dielectric properties of sheet mica. This procedure led to an all-time high use of small-sized mica, which further depleted U.S. reserves and increased imports of mica from India. Small-sized material was used as insulators in electric motors, spark plugs, and magnetos in gasoline engines, and as a sound diaphragm in phonographs. Wet-ground mica was used in wallpaper, and coarsely ground material was used as artificial snow. Dry-ground mica was used primarily in the rolled roofing and asphalt industry to prevent sticking, and was also used as an additive in axle grease and special lubricants (Hedrick, 2002).

The development of the vacuum tube during 1904 (Tanner, 1994), its use in radios during and following World War I, and the development and use of sophisticated electronic equipment during World War II, maintained the demand for mica (figs. 8 and 9). At that time the United States was almost wholly dependent on imports for split mica. British India dominated the field of muscovite splittings, largely because its cheap labor force could produce splittings at a fraction of their cost elsewhere. Also, there were prejudices against using domestic mica for condensers, radio tubes, and some even less exacting uses (Tyler and Warner, 1941).

The demand for sheet mica dropped off dramatically after WWII, and U.S. Government programs that were initiated during WWII to develop mica were terminated (Tanner, 1994). Resources for Freedom (The President's Materials Policy Commission, 1952) predicted that during the period from about 1950-1975, hand-split mica would largely be replaced with built up mica, high-temperature plastics, and glass-fiber substitutes, and the commission made no efforts to estimate reserves for strategic mica. Nevertheless, there were government programs to stimulate mica production. For example, the Government Purchasing Depot at Custer, South Dakota, created a market for hand-cobbed and block mica. From 1954-1955, New Mexico experienced a nearly-five-fold increase in hand cobbed mica production, with much of that production going to the depot at South Dakota, (Kelly and others, 1958). The domestic mica purchase program for strategic stockpiles was terminated in 1962 (Tanner, 1994), and in 1966 President Lyndon Johnson signed a bill authorizing disposal of excess stockpile commodities, which included mica (Woolley and Peters, 2007).

During the 1950s and 1960s transistors gradually replaced vacuum tubes, thus significantly reducing the demand for sheet mica. The situation was further exacerbated with the evolution of synthetic substitutes and the advancement of solid state electronics beginning in the 1970s (Tepordei, 1981; Chapman, 1983). Production of sheet mica in the U.S. ended in 1976.

Today the U.S imports approximately 32 percent of its scrap and flake mica from Canada, India, China, and other countries, listed in descending order. Nearly half the U.S. production of flake mica comes from North Carolina. The U.S. imports 100 percent of its sheet mica from India, Belgium, China, Brazil, and other countries, listed in descending order. Many manufactured materials can be substituted for mica in electrical and insulation uses.

Perlite

> "Production of expanded perlite, a material virtually unknown on a commercial basis before World War II, was 33 times greater in 1951 than in 1946." (North, 1954, p. 1376).

"Perlite is a glassy volcanic rock which will, upon rapid controlled heating, expand or 'pop' into a frothy material of low bulk density, valued as a lightweight aggregate." (Chesterman, 1975, p. 927). The term perlite applies to the rock and the expanded product. No industrial mineral better demonstrates the speed with which a new mineral can successfully be brought into the market than perlite.

There are two anecdotal stories that describe the discovery of the expansive properties of perlite. One reports that sometime around 1941, an American dentist experimenting with tooth enamels discovered that a certain kind of rock expanded when heated. Another story is that, at about the same time, a geologist put out a bonfire on the beach of Milos Island, Greece by throwing beach sand on it. “The ensuing pyrotechnic display immediately conjured up in the man’s mind the possibility of a new use for the volcanic rock that constituted most of the island.” (Kadey, 1983b, p. 997).

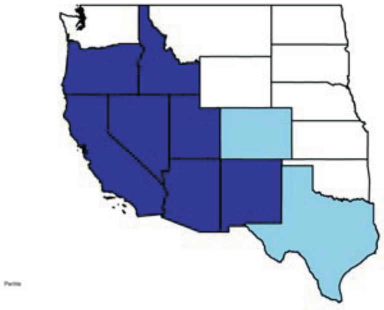

Figure 11. Western States where perlite was produced in 2004 (dark blue), or previously has been produced (light blue).

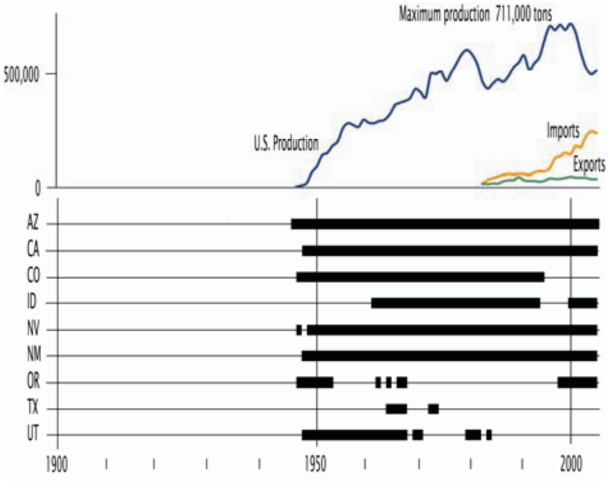

Figure 12. Bar graph showing periods of perlite production in western States, and line graph showing U.S. production, exports, and imports, from 1905-2004.

Modern perlite production began during 1946 in Superior, Arizona. Five companies reported production; most from the Superior area and one from near Beatty, Nevada. All of the material sold in 1946 was used by the construction industry as thermal insulation and lightweight aggregate (Bolen, 2002). Soon thereafter production began in New Mexico and other western States (Barker and Santini, 2006). New Mexico has been the major perlite-producing State ever since, and produces the vast majority of U.S. perlite.

The building boom following World War II helped perlite gain market share in competition with expanded slag, clay, vermiculite, and other lightweight materials (Bolen, 2002).

Nine companies reported sales in 1948; 63 companies reported sales two years later. By the early 1950s perlite markets were well established (Breese and Barker, 1994). Perlite became a chapter in Minerals Yearbook in 1952, and was included as a chapter in the 4th Edition of *Industrial Minerals and Rocks,* (Chesterman, 1975).

Domestically, economic deposits of perlite occur only in western States, making transport to eastern markets a significant factor. Attempts to export Greek and Icelandic perlite to the east coast of the United States in early 1960s failed for anumber of reasons including lack of warehouse space for boatloads of crude perlite (Kadey, 1983b). However, during 1980, Greece became the world's leading exporter of processed perlite. Greece began exporting to the east coast of the U.S. during 1983; perlite from Greece accounted for about 7 percent of U.S. consumption (Meisinger, 1984). This marketing strategy was possible in part due to "just-in-time" warehouses that receive deliveries only when needed, thus avoiding the requirement for large inventories (Barker and Santini, 2006).

In the 21st century growth in the U.S. perlite industry has been slow but steady, and the industry is consolidating into fewer and larger firms. During 2005, the U.S. imported 24 percent of its perlite from Greece. Greek imports can continue to economically supply Midwestern and east coast markets because of high rail rates from western U.S. mines (Breese and Barker, 1994).

Potash

> "Practically all the potash salts of mineral origin consumed in the American industries at present are imported from abroad, chiefly from Germany. … [T]he comparative cheapness of foreign potash, tend[s] to destroy the domestic industry." (Phalen, 1911, pg. 747-748).

Nearly 100 years later, imports continue to effect the potash industry.

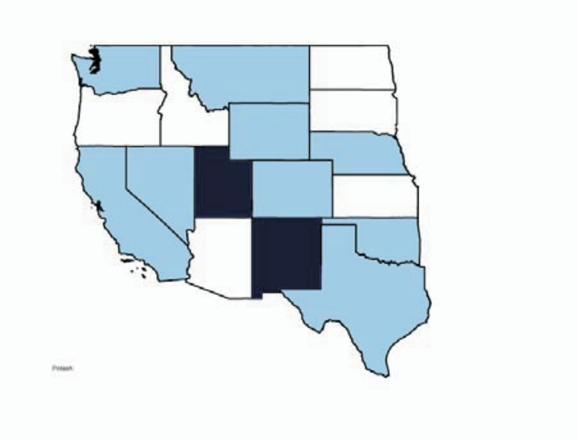

Figure 13. Western States where potash was produced in 2004 produced (dark blue), or previously has been produced (light blue).

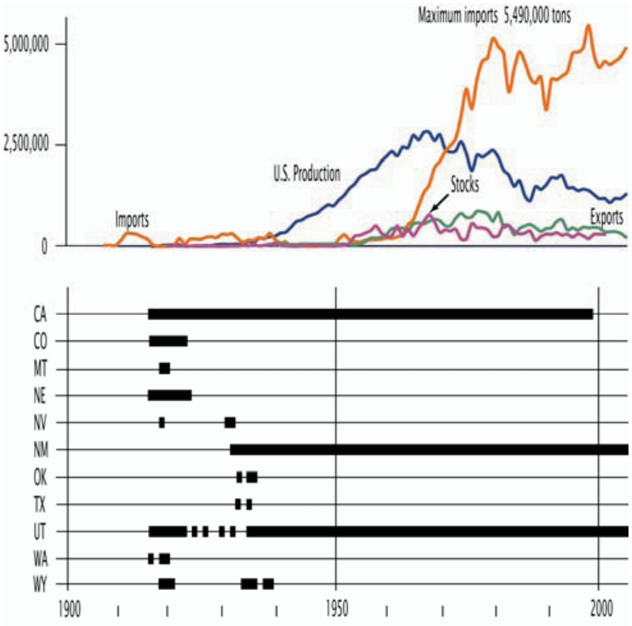

Figure 14. Bar graph showing periods of potash production in western States, and line graph showing U.S. production, exports, imports, and stockpiles, from 1905-2004.

The word potash is a compound of "pot" and "ash," reflecting how the salts were first made by soaking wood ashes from broad-leafed trees in pots of hot water. In 1870, a mineral source of water-soluble potassium was found in Germany, which made Germany the world supplier of potassium chloride (Searls, 2002). During WWI, Germany ceased exporting potassium chemicals to the United States. Potassium was used to manufacture potassium nitrate, an oxidizer in munitions and signaling rockets, and for the solid oxidizer potassium permanganate in gas masks. To meet wartime needs, numerous potassium salt resources were developed including subsurface brines in California, lake brines in western Nebraska and Utah, the dust of cement plants and iron refineries, molasses refinery waste, wood ashes, and kelp (Searls, 2002).

The serious shortage of potash during World War I inflated its price (Hedges, 1941). Congress allocated money to stimulate the study of potash resources in the U.S. The potash deposits of Germany and France had been discovered accidentally during the boring of deep wells in search of other minerals (Nourse, 1923), and geologists exploring for oil and gas in the U.S. were encouraged to watch for potash. During 1925, an oil exploration team in New Mexico noted potash in a well east of Carlsbad. A shaft was sunk and considerable work was done on those deposits in 1930 (Coons, 1932). Potash production commenced in 1932, and three mines were operating in New Mexico by the beginning of WWII (Searls, 2002). To place production in perspective, in 1930, U.S. imports of potash were more than 5.5 times domestic production (Coons, 1932); during 1939 domestic production was three times greater than imports (Hedges, 1940). “This fortunate situation is directly attributable to the foresight that led the Federal Government to pioneer in the search for potash resources and to encourage and foster the building of a domestic industry that can now supply cheaply all the potash required to meet essential needs.” (Hedges, 1940, pg. 1387).

From 1941-1949, domestic production provided virtually all potash in the U.S. (Barker and Austin, 1996). During 1950, the discovery of potash in a deep well in Saskatchewan, Canada was announced (Johnson and Jensen, 1953). During the 1950s and 1960s, New Mexico, California, and Utah (in decreasing order) provided essentially all the U.S. production of potash, with New Mexico regularly providing more than 90 percent of that production. During 1960, domestic production of potash was 11.5 times greater than imports. But the potash industry dramatically changed during 1964 because potash was first successfully produced using solution mining from the potash area in Saskatchewan (Lewis, 1965). Potash production in the U.S. reached a peak in 1966, but a general decline in production began that same year due to the large imports from Canada (Eilertsen, 1972). The worldwide market for potash has been in a situation of oversupply since the 1980s (Prud'homme and Krukowski, 2006).

During 2005 approximately 80 percent of the potash consumed in the United States was imported, most of that coming from Canada. During the past one hundred years the U.S. has gone from being totally dependent on foreign sources for potash, to being nearly self-sufficient, to again being heavily dependent on foreign sources. However, large resources exist in the U.S. (Kostick, 2006) should the need to be self-sufficient arise again.

Summary

The U.S. Geological Survey conducts surveys and reports on the production of about 42 industrial minerals. Thirty two of these industrial minerals are, or have been, produced in the 17 western states of Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming. Some commodities, such as sand and gravel, currently are produced in all 17 states; others such as beryllium, boron, and iodine are produced in only one state, Utah, California, and Oklahoma, respectively. The production history of six of these industrial minerals (diatomite, feldspar, mica, manganese, perlite, and potash) demonstrates some of the social or environmental issues that influence the industrial mineral industry.

Diatomite is clearly a western-State industrial mineral, with the total U.S. supply currently coming from California, Nevada, and Oregon. Because of its versatility as a filtering agent, it has shown nearly continuous growth over the past hundred years.

Production of feldspars in the U.S. is primarily from eastern States; however, seven western States had substantial periods of feldspar production, and three others have had sporadic production. The feldspar industry is characterized by ups and downs in production and capacity caused by variable demands of the building industry, technological advances, and the availablity of substitutes for the product.

Production of fluorite in the U.S. began in western States but soon was dominated by mines in Illinois and Kentucky. Competition from foreign sources and environmental regulations on CFCs led to termination of fluorspar mining in most western States during the 1970s, and termination of all remaining U.S. fluorspar mining operations during 1996.

The United States has nearly continuously been dependent on foreign sources for high quality manganese ore. Government programs designed to develop U.S. supplies supported production of manganese in all western States except Kansas, Nebraska, and North Dakota. Nevertheless, the U.S. currently imports 100 percent of the manganese it consumes.

The U.S. led the world in the production of mica during the mid-19th century because of demand for use in stoves with mica “windows” rather than open fireplaces. But the high cost of hand-processing, classifying, trimming, and splitting mica, especially sheet mica, has created a great disadvantage for domestic production trying to compete with low-cost producing foreign countries. Although domestic sources of mica are numerous, large size material does not occur in the United States in substantial quantities. Most flake mica produced in the U.S comes from North Carolina; the U.S. produces no sheet mica. South Dakota and New Mexico currently produce relatively small amounts of flake mica; nine other western states previously produced mica.

Perlite is another industrial mineral where historical production has been dominated by western States. Seven western States currently produce perlite. Two other western States used to produce perlite. The majority of U.S. perlite is produced in New Mexico. Perlite is a high bulk, low value commodity, and transportation can constitute a large part of the delivered price. Consequently, some of the markets east of the Mississippi import perlite produced in Greece.

At the beginning of the 20th century, the U.S. was dependent on potash imported from Germany. Shortages during World War I resulted in the development of potassium salt resources including subsurface brines in California and lake brines in western Nebraska and Utah. Following the World War I, government programs were begun to encourage identification of domestic sources of this important commodity. During 1925, an oil exploration team in New Mexico noted potash in a well east of Carlsbad, N. Mex. Potash production commenced in 1932, and during the 1940s virtually all U.S. potash was produced domestically. Potash production in the U.S. reached a peak in 1966, but a general decline in U.S. production began that same year due to the large imports from Canada produced using solution mining from the potash area in Saskatchewan.

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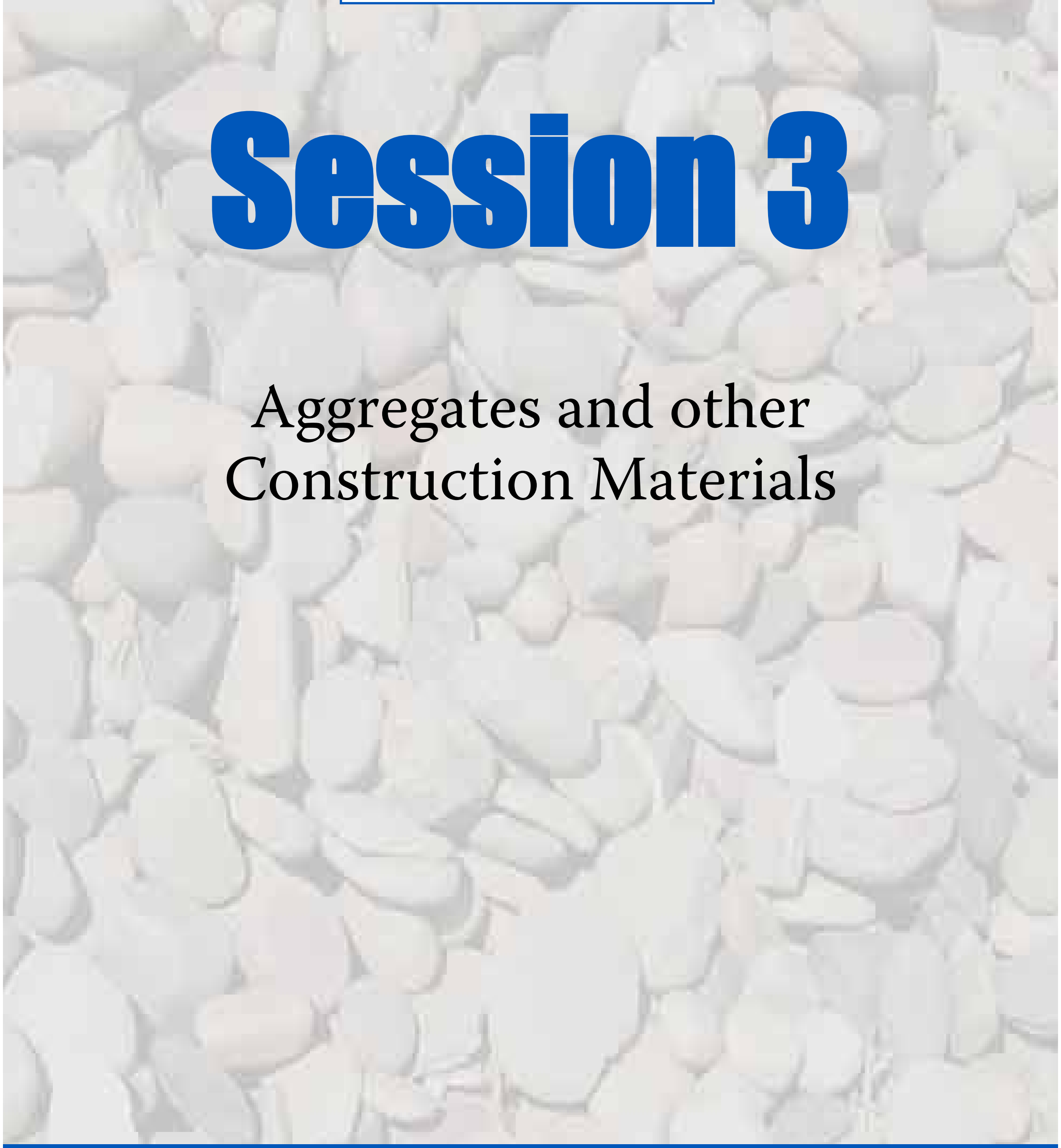

Session 3

Aggregates and other Construction Materials

The Economic Geology of the Ovruch Quartzite and Sandstone Deposits Northern Ukraine –Transition from Soviet Controlled Operations to Free Market Enterprises

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ABSTRACT

The Ovruch quartzite and sandstone deposits are located in the northwest part of the Ukrainian shield and in the central part of the Slovechan-Ovruch synclinal feature. The quartzite deposits of economic interest in the Ovruch area are Proterozoic in age and the overlying sandstone deposits of economic interest are Pleistocene (middle Quaternary) in age. Mining of quartzite for decorative applications began around 980 AD and continues to the present. Other applications for the quartzite include the following:

- Raw material for fireproof brick and ferroalloy in ferrous metallurgy.
- High-aluminum-content portions of the deposit are unsuitable for metallurgical applications but are used as aggregate.

The overlying sandstone meets specifications for the following:

- Foundry sand applications
- Fiberglass production
- Filtration uses

There are two producing companies in the Ovruch area whose annual output of quartzite mined by open pit methods during the Soviet era was about 10 million tons. In recent times output from these mines has dropped to around 1.2 million tons annually. The fall of the Soviet Union resulted in the loss of markets due to non-competitive transportation infrastructure; quality control issues with applications in ferrous metallurgy; changes in steel making technology due to modernization of steel mills; and utilization of metallurgical-grade quartzite from mines in closer to the steel mills. In order to widen the product line with a potentially more valuable industrial mineral, the sandstone deposit overlying the quartzite was investigated for its suitability in a wide variety of applications. Ongoing evaluations of the sandstone and development of high value products coupled with the development of new markets in Western Europe for the quartzite have enabled these formerly Soviet-controlled companies to begin the difficult transition to profitable organizations in the free market.

INTRODUCTION

The Zhytomyr region of northern Ukraine near the city of Ovruch is the site of two quartzite quarries - the Ovruch quartzite quarry and processing plant owned by JSC Danko and the Tolachevskiy quarry and processing plant owned by Privat Bank. The Ovruch quarry was developed in the mid-1930's by the Soviet Union to supply refractory brick and ferroalloy products to steel making facilities throughout the USSR. The nearby Tolachevskiy quarry was developed to provide building cladding and road base materials to local markets. The Ovruch Quarry under the Soviet command economy was designated as the sole supplier of quartzite to all facilities making steel, even those as far away as Uzbekistan. The quarry was not allowed to produce any quartzite for local road or construction applications. The Tolachevskiy Quarry was designated as the sole supplier of construction and road base material for local markets and was not allowed to produce any quartzite for the steel markets. The quality of the quartzite is the same for both quarries.

With the breakup of the Soviet Union, these two quarries were privatized and began competing with each other. Additionally, the Ovruch quarry lost most of the markets outside of Ukraine because of high transportation costs, development of quartzite deposits closer to the steel making facilities, and the modernization of facilities that did not use quartzite in steel making.

Both quarries have taken significant steps to modernize their facilities and to develop new markets. The Ovruch facility is developing a sandstone deposit, which overlies the quartzite for use in fiberglass, foundry sand, and filtration applications. The Tolachevskiy facility is expanding its processing capability to supply steel-making facilities and also expanding marketing of their road and construction material sales to take advantage of the booming construction activity in and around Kiev.

LOCATION

The Ovruch and Tolachevskiy quarries are located in the Zhytomyr of northern Ukraine adjacent to the mining village of Persotravneve approximately 5 kilometers north of the city of Ovruch and 5 kilometers south of the Belarus border (figs. 1 and 2).

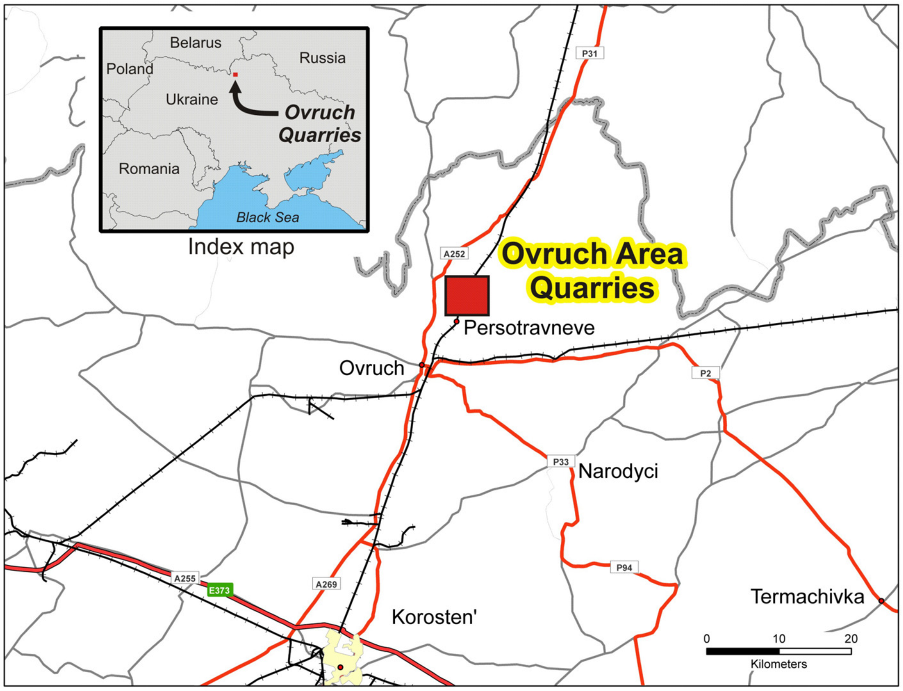

Figure 1. Location Map, Ovruch area quarries.

Figure 2. Google Earth image showing the Ovruch and Tolachevskiy quarries.

HISTORY

The first significant use of quartzite from the Ovruch area was in a building cladding mosaic on the late 12th century Saint Vassiliy Russian Orthodox Church in Ovruch (fig. 3). In the proceeding centuries up to modern times the quartzite was commonly used as building cladding, and in walls and fence posts (figs. 4 and 5).

Figure 3. Mosaic of quartzite in 12th century St. Vassiliy Russian Orthodox Church.

Figure 4. Quartzite used in fence wall construction.

Figure 5. Quartzite in use in fence post and wall construction.

In the early 1930s, the area of the Ovruch and Tolachevskiy quarries was explored and drilled by Soviet geologists and in 1936 the quarries began operations. Also at this time the village of Persotravneve was established and mine personnel were moved in (figs. 6, 7, and 8).

Figure 6. Village of Persotravneve, Main Street.

Figure 7. Russian Orthodox Church showing quartzite wall, Village of Persotravneve.

Figure 8. Typical older house, Village of Persotravneve. Note road base stockpile of quartzite in lower left of photo.

During World War II the quarries were shut down, and were reopened after 1945. The quarries have been in continuous operation since World War II. The quarries are located in the so-called “dead zone” within the fall-out depositional area of Chernobyl. In 2000, the village and mining areas were evaluated and declared free of radiation by the UN and by the Ukraine Ministry of health Care (JSC Danko, 2004).

GEOLOGY

The Ovruch and Tolachevskiy deposits of quartzite are located in the northwestern part of the Ukrainian crystalline shield, and in the central part of the Slovechan-Ovruch synclinal structure. The Slovechan-Ovruch structure represents a synclinal basin known as the Ovruch graben. The basin is filled with variably metamorphosed sedimentary deposits of Proterozoic age. The deposits consist of quartzite, sandstones, and pyrophyllite shale of the Tolkachev Formation of the Ovruch Series, which overly sediments of Zbrankov Formation. The youngest exposed sediments lie on the eroded surface of magmatic ultra-metamorphic deposits of Korostensk, Kirovograd, Zhitomir and Osnizck complexes of Early Proterozoic age. Twenty kilometers to the west of the deposits, the maximum thickness of Tolkachev Formation reaches 932 m. Sediments of the Tolkachev Formation fill a synclinal structure and are traced as latitudinal strata for more than 100 km in length. The width of the strata changes from 25 km in the west to 9 km in the east. Detailed drilling and geologic work showed a bed of relatively homogeneous quartzite from near the surface to a depth of 80-100 m.

Stratigraphy of the Deposit

Late Quaternary – Holocene sediments

Quaternary deposits are widely represented except in the areas where more ancient deposits appear on the surface. The thickest layers of Quaternary deposits occur in river valleys and outwash valleys. Quaternary deposits mostly consist of sandy clays, silts, fluvioglacial alluvium, and eolian sediments. Primarily they are of glacial origin. Quaternary deposits are represented by sandy loams with boulders, loess, loess loam, silt and peat. This zone varies from 2 to 4 m in thickness.

Pleistocene (middle Quaternary) sandstone

Pleistocene sandstone deposits consist of rounded quartz sand grains, light yellow to white in color, gravel, and boulders of sandstone and quartzite. This zone varies from 4 to 8 m in thickness with 4 m being the average (figs. 9 and 10). A major unconformity separates the Pleistocene deposits from the underlying rocks of the Tolkachev Formation.


Figure 9. Pleistocene sandstone.

Figure 10. Pleistocene sandstone at unconformity overlying Proterozoic quartzite.

Tolkachev Formation

The Tolkachev_Formation consists of sandstones, quartzite, pyrophyllite, and pyrophyllite-quartz-crystalline shale of sedimentary genesis. The formation underlies the entire Slovechan-Ovruch deposit area where they form a 100 km-long latitudinal syncline. The maximum thickness of the Tolkachev Formation, according to the data from a nearby drill hole, is 932 m. At the quarry site the thickness is approximately from 300 m to 600 m. The thickness increases from east to west. Tolkachev deposits are represented by pink, pinkish-reddish, crimson red, less common light pink, gray quartzite, quartzitic sandstones with layers and separate lenses of pyrophyllite shale and pyrophyllite-quartz-crystalline shale. The quartzite has a greater degree of metamorphism than the sandstones. It has the same color as the sandstones but has compact and semi-compact, massive texture. Macroscopically, individual grains of quartz are indistinguishable. Figure 11 shows the geology of the Ovruch deposit.

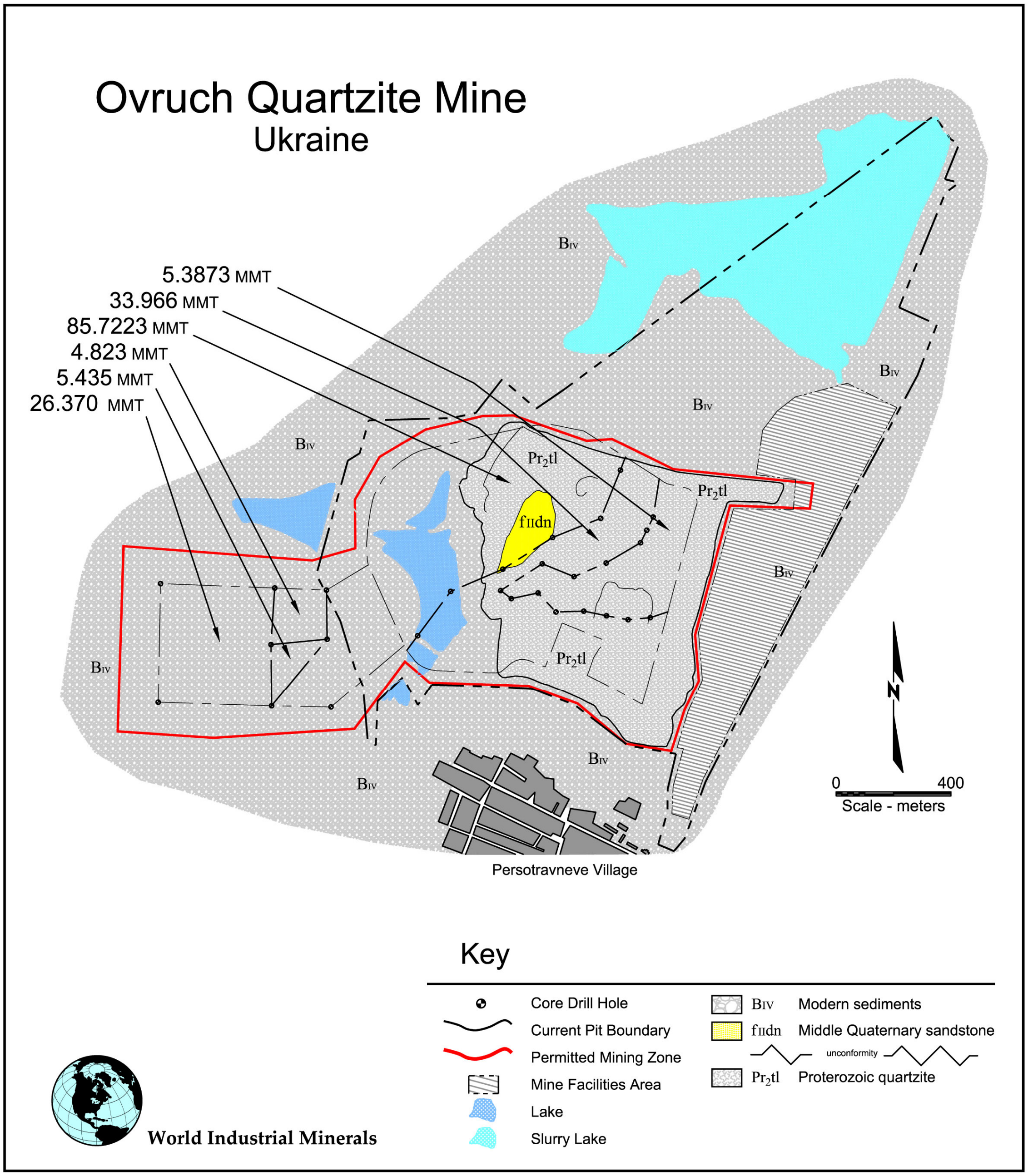

Figure 11. Geology of the Ovruch quartzite mine.

The geology of the Tolkachev deposit is similar to the Ovruch except that there are no overlying Quaternary or Holocene sediments. Additionally, there is a large fault that cuts through the center of the quarry that causes problems with the stability of the pit walls (UMRSK, 1980). The fault and associated fracturing has, however, caused much of the quartzite to breakup into relatively uniformly sized blocks and pieces (as seen in the building cladding pictures) that can be easily quarried for decorative and building cladding uses (fig. 12 and 13).

Figure 12. Tolachevskiy quarry showing faulted zone where blocks are mined for decorative stone.

Figure 13. Tolachevskiy quarry, hand sorting of quartzite blocks for decorative stone use.

RESERVES AND RESOURCES

Reserves and resources were developed under Soviet ore reserve estimation procedures. Ore reserves developed to date were drilled in detail from 1980 to1984. Currently there are explored reserves within the 300 hectare mining boundary of 150 million tons of quartzite of which 10.5 million tons is developed. All reserves are within a zone from near surface to a depth of approximately 80 m (JSC Danko, 2004). Reserves for the various mining blocks are shown on Figure 11.

QUARTZITE SPECIFICATIONS AND PRODUCTS

Quartzite has massive texture and consists mainly of quartz. The composition of the quartzite is as follows:

Quartz: 96 to 98.9%
Quartz porphyry (clasts): 0.5%
Pyrophyllite: 0.5%
Iron: 0.4 - 0.6%
Alumina: 1.3 to 1.6%

Quartzite is used as a raw material for fireproof brick and ferroalloy in ferrous metallurgy. High aluminum content in pyrophyllite-quartz shales make them unsuitable for metallurgy but they can be used as raw material for production of crushed rock aggregate. Thin layers and lenses of pyrophyllite shale are found in the lower part of strata. Their thickness is no more than 10-20 cm. They are soft, grayish-red, clay-like beds. Below 80 m, the aluminia content becomes too high making the quartzite unsuitable for use in steel-making applications. Until the fall of the Soviet Union, annual output from the mine was around 3 million mt. In recent years, shrinking markets have been responsible for steep declines in production to around 1 million t annually. In addition to the seven major silica and metallurgical products produced, the mine also produces byproduct construction stone and road base products. Approximately 160,000 t of these construction materials are sold annually to local contractors (JSC Danko, 2004).

The quartzite from the Tolachevskiy quarry is used primarily for road base construction and building cladding applications. Figure 13 shows local contractors sorting and loading quartzite pieces for building cladding. For decorative applications, the annual quarry output is small; around 3,000 t. Production of road base and construction materials is around 300,000 t annually (Privat Bank, 2004).

QUARRYING

The Ovruch quarry layout is typical of a quarry pit developed for the mining of a massive, flat lying, and shallow ore body in flat terrain. Overburden is shallow (4-8 m) and is easily removed by a stripping rope shovel (excavator) equipped with a five-cubic-meter bucket, without blasting. The overburden is hauled to the waste dump in 30- or 40-ton trucks.

Fifteen-meter-high quarry benches are developed through the use of electric rotary blast-hole drills. Tri-cone rotary drill bits are used to drill a typical blast pattern of approximately 40 250-mm blast holes spaced on a five-by-five-meter pattern. ANFO is the primary blasting agent.

The operation suffers from the blasting agent being of poor quality, resulting in considerable secondary blasting of oversize material. The issue of poor explosive quality is not localized to the Ovruch quarry, as poor quality was also described as a problem at the neighboring Tolkachevskiy quarry.

Electric crawler-mounted mining and quarrying rope shovels (excavators) have a five-cubic-meter bucket to load broken ore. The quarry has a total of five shovels available for quarry duty, and if required, three additional shovels are available from the product loading areas of the mill. This allows the quarry a great luxury in production scheduling; deferring machine maintenance and lowered investment in spare parts inventories (fig. 14).

Figure 14. - Upper photo: Haul trucks in Ovruch quarry.
Lower photo: Electric excavator loading quartzite into haul truck.

Ore is hauled to the mill in mechanical drive, 30- and 40-ton Belurussian-manufactured rear-dump trucks. The haul fleet is comprised of 14 trucks (nine 30-ton and five 40-ton). At least four of the 30-ton trucks appeared to be captive to the milling operation, hauling intermediate product between the main plant and either the ground product or road base sections of the facility.

The Tolachevskiy quarry has similar mining equipment but less of it because it is a smaller operation. Mining methods are also similar except for the building cladding quarrying in which quartzite fragments loosened from the pit walls are hauled to the center of the quarry for local contractors to pick through a haul off (Christopherson, 2004).

PROCESSING

Ore from the quarry is dumped into one of two dump hoppers, which feed two jaw crushers, each having a 350-tph capacity. These crushers are located in a brick building, below ground grade. The building and crushers are conventional in design, configuration, and usage of equipment. From the primary crushers ore reports to a secondary cone crusher, having conventional design and usage. The crushed quartzite is then wet screened to desired product size and then conveyed to discrete storage bunkers for either shipping or for additional processing into either a ground quartzite or road base product. Washed fines are captured in two spiral classifiers and allowed to flow into a large impoundment.

Material in the 5-25 mm size range is loaded and hauled in 30-ton trucks a short distance to a hopper feeding a separate production line. This line produces a ground quartzite, or a product containing a mixture of ground quartzite and clay. This circuit was designed to utilize a cone crusher for fine crushing of material, before discharge to two ball mills for fine grinding. Finished product is packaged into “big bags” containing about one ton of finished product (fig. 15). A bridge crane is utilized to load rail cars on a dedicated siding (fig. 15). A third product line also receives 5-25 mm material delivered in 30-ton trucks. This product line utilizes an impact-style crusher to produce a cubic shaped quartzite product for road base applications and other construction related uses. Crushed material is screened to required specifications, loaded into “Big Bags” and transported to a rail loading area, or placed directly into trucks for transport to a rail stockpile area, where a front-end loader loads into rail cars; product is also loaded directly into other trucks for customer delivery. Finished product from the main crushing and washing section is loaded into open-top gondola rail cars via electric quarry shovels.

Figure 15. Upper photo: Train car and “big sack” quartzite loading area.
Middle photo: Processing plant and quartzite storage area.
Lower photo: Covered conveyor system depositing sized quartzite products.

The Tolachevskiy quarry has similar, smaller capacity processing equipment. The operation is adding additional crushing equipment to augment the increased quartzite production for steel-making companies (Christopherson, 2004).

NEW PRODUCT DEVELOPMENT

To enhance the value of the Ovruch quarry quartzite, a review was undertaken of possible new markets that could utilize the quartzite and other rocks present at the mine. Additionally, a review was made of the potential of enhancing products currently sold in order to increase sales margin. Because of the pervasive high iron content near 0.6 percent and the high alumina content near 1.5 percent, no new applications were identified for which the quartzite was suitable. The inability to lower either the iron or alumina content of the quartzite removes the rock from consideration for markets other than for those it currently meets specification.

During the field examination of the quartzite in the quarry an overlying sandstone unit (designated f_{II}dn) on the map was also studied. This sandstone consists of white to tan to yellow rounded grains containing streaks of what appear to be iron oxide coatings on the grains. This sandstone unit at one time completely overlaid the quartzite that was mined from the quarry and all areas surrounding the pit. Within the quarry it was it was estimated that there was 1.2 million tons of sandstone in the small island left in the center of the quarry (see fig. 11 for sandstone [f_{II}dn] location). Additional tonnages are found in the stockpile areas and within the un-mined areas of the mining permit boundary (red boundary on map). It appears that the sandstone has been stockpiled in an area to the north and west of the pit along with the overlying modern sediments (Biv unit on map). No estimate of tonnages outside of the current pit area has been made but several million tons are inferred based on drilling completed to date.

Analysis of this raw sandstone gives the following range of values (JSC Danko, 2004):

Sample #	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	LOI (%)
1	98.06	1.15	0.16	0.44
2	98.16	0.95	0.25	0.40
3	98.80	0.71	0.09	0.27

It should be noted that this sandstone, unlike the quartzite, is potentially amenable to processing for enhancement of silica grade and lowering of alumina and iron contents through attrition scrubbing and or acidizing.

The following is a list of applications and associated specifications for which the sandstone may be suitable.

Foundry Sand- AFA 70/80: Spanish-International Foundry Industry Specification
SiO_2 : 97.85%
Fe_2O_3 : 0.133%
Al_2O_3 : 0.946%
Grain Shape : Rounded

Fiberglass – US-International Standard Specification
SiO_2 : 98.5 – 99.0%
Fe_2O_3 : 0.3% Maximum
Al_2O_3 : 0.2 – 1.6%

Filtration – US-International Standard Specification

Silica sand used as a filter must be clean (free of dust, clay, micaceous material, and organic matter) and the individual sand grains must be between 0.15 to 0.35 mm in diameter. Grain shape should be angular to round but not flat or elongated. Particle size distribution specifications as to effective size and uniformity coefficient are also required for specific end-market uses. (Harben 2002)

Refractories – US-International Standard Specification

Refractories: requires sand with a 95 to 99 % SiO_2 content plus 1.5 to 2% lime to convert the quartz to cristobalite and tridymite in a silica refractory brick. (Harben, 2002)

Construction – US-International Standard Specifications

- Well Pack – sub-rounded quartz grains
- Concrete Sand – minimum 96% SiO_2
- Mason Sand – minimum 96% SiO_2
- Recreation/Traction Sand – minimum 97% SiO_2; sub-rounded to sub– angular; buff to white in color.

Currently JSC Danko, owner of the Ovruch quarry, has purchased equipment for processing the sand for fiberglass manufacturing, and is pursuing local construction markets.

SUMMARY

With the breakup of the Soviet Union, former state run monopolies such as the quartzite quarries in northern Ukraine were forced to adopt free-market business development strategies in order to survive. JSC Danko, owner of the Ovruch quarry, lost significant market share when steel-making companies outside of Ukraine would no longer buy their product. Their response to these changes in market conditions was to develop new quartzite product lines for the local construction and road base markets (in direct competition the Tolkachevskiy quarry) and to test and develop a previously unrecognized asset, the overlying silica sand, for new and potentially more profitable fiberglass product lines.

On the other hand, with the break up of the Soviet Union, Privat Bank saw an opportunity to expand their Tolkachevskiy quarry operation by providing lower-cost products to the steel-making facilities in Ukraine in direct competition to the higher cost Ovruch operation.

To survive and capitalize on new opportunities both companies have had to modernize their operations by replacing aging equipment, construct additional processing facilities, and develop market share. It has been a painful transition for both companies but in the long run each is a healthier, more efficient operation that should continue to prosper in this dynamic new environment.

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How Geology and Gravel Composition Affect Aggregate Quality in the South Platte River and its Tributaries, Colorado

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ABSTRACT

Alluvial sand and gravel is a major source of aggregate for construction in northern Colorado east of the Front Range. More than half of the aggregate produced in this area comes from gravel pits in alluvium of the South Platte River and its tributaries.

Alluvial sand and gravel in the valley of the South Platte River and its main tributaries near Denver is typically about 20-40 feet thick. Downstream near Greeley, South Platte alluvium may reach 100 feet. The valley also widens downstream to as much as 5 miles, so that the volume of sand and gravel available for mining is much larger than upstream. Near the mountains, thick deposits of sand and gravel also fill old valleys beneath alluvial fans. Old valleys beneath the Rocky Flats fan contain as much as 100 feet of sand and gravel, although thicknesses above buried ridgelines are much less.

The coarseness of gravel—expressed by maximum or mean particle size or by size distribution—is greatest near the mountain front. Particle size, and the ratio of gravel to sand, gradually decreases downstream, limiting the availability of sufficiently coarse product. While particle size decreases downstream, the proportion of inter-bedded fine sediment (fine sand, silt and clay) increases. Like overburden, some beds of fine-grained sediment must be stripped before mining can proceed. Other obstacles embedded in gravel and requiring removal include large logs and accumulations of plant debris.

Stream source also affects particle size. Streams that head in the mountains produce coarse gravel by eroding hard bedrock. For the most part, streams that head in the plains only erode soft rock and sediment. Unless hard bedrock or coarse gravel is available locally for recycling, deposits of plains streams are fine-grained.

Gravel lithology—the composition of individual particles—affects the Los Angeles degradation value of gravel. Quartz and quartzite, common in some gravel, are the hardest; sandstone is the softest. A dispersion train of recycled quartzite extends about 40 miles from the mountain headwaters of Coal Creek, located at the head of the Rocky Flats fan, to the low hills east of the South Platte River. Gravel from the South Platte and Cache la Poudre valleys is low in quartz and quartzite, but contains sufficient quantities of hard granitic rock to give it durability for use as construction aggregate.

Weathering takes its toll on aggregate quality in old gravel. The more than one-million-year-old gravel of Rocky Flats is deeply and thoroughly weathered, so that most particles except quartz and quartzite disintegrate to sand and finer particles during mining. Weathering reduces the proportion of suitable aggregate that can be produced and leaves large amounts of fine-grained sediment for disposal. In contrast, younger gravel, commonly less than 30 thousand years old, has not been subject to significant disintegration by weathering.

INTRODUCTION

The valleys of the South Platte River and its tributaries contain large deposits of gravel used for construction in the Front Range Urban Corridor (fig. 1). The South Platte River valley north of Denver and the valleys of Boulder Creek, St. Vrain Creek, the Big and Little Thompson Rivers, and the Cache la Poudre River currently produce more than half of the aggregate used in the Urban Corridor. In the Denver metropolitan area, and within the limits of other Front Range cities, most of the gravel has been mined or precluded from mining by urban development. North of Denver, gravel mining has steadily moved downstream into sandy gravel deposits (compare Schwochow and others, 1974a with Hemborg, 1996; Lindsey and others, 1998). When the gravel deposits of the South Platte and its tributary valleys have been exhausted or preempted by other land use, aggregate for the Denver area will by necessity come from stone quarries in the mountains.

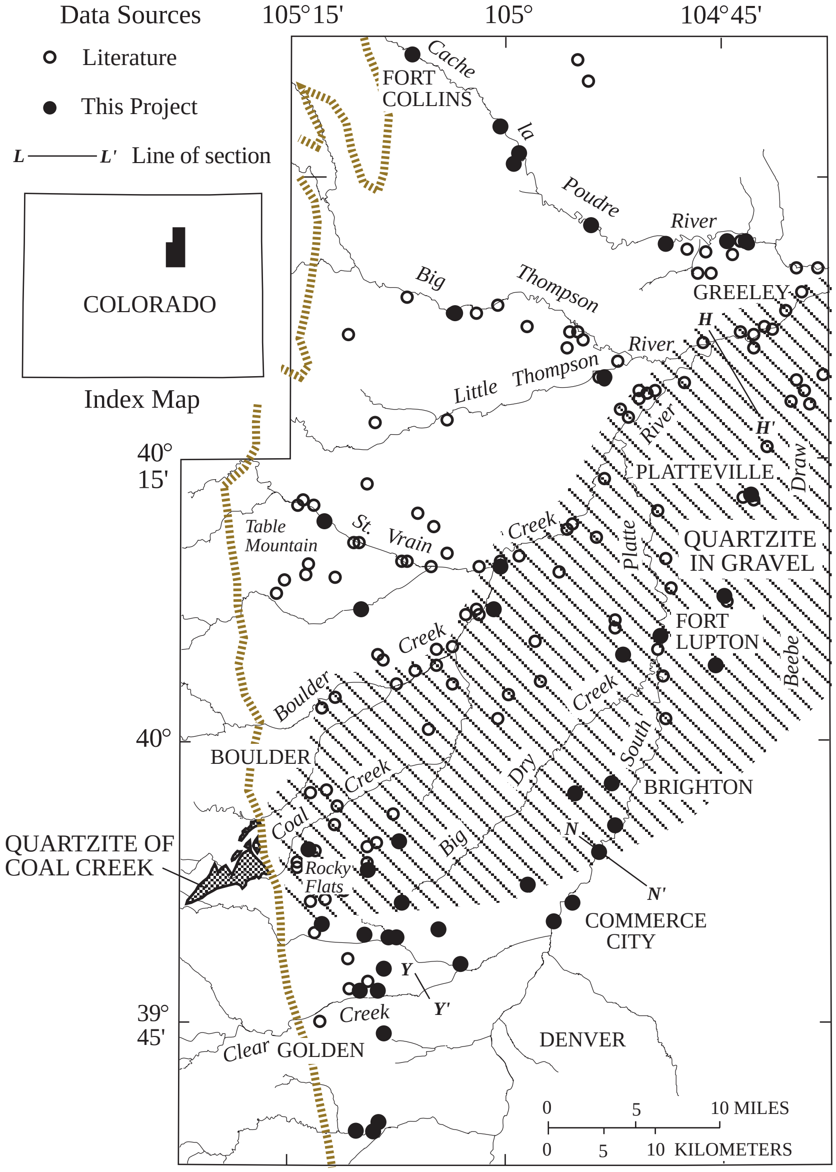
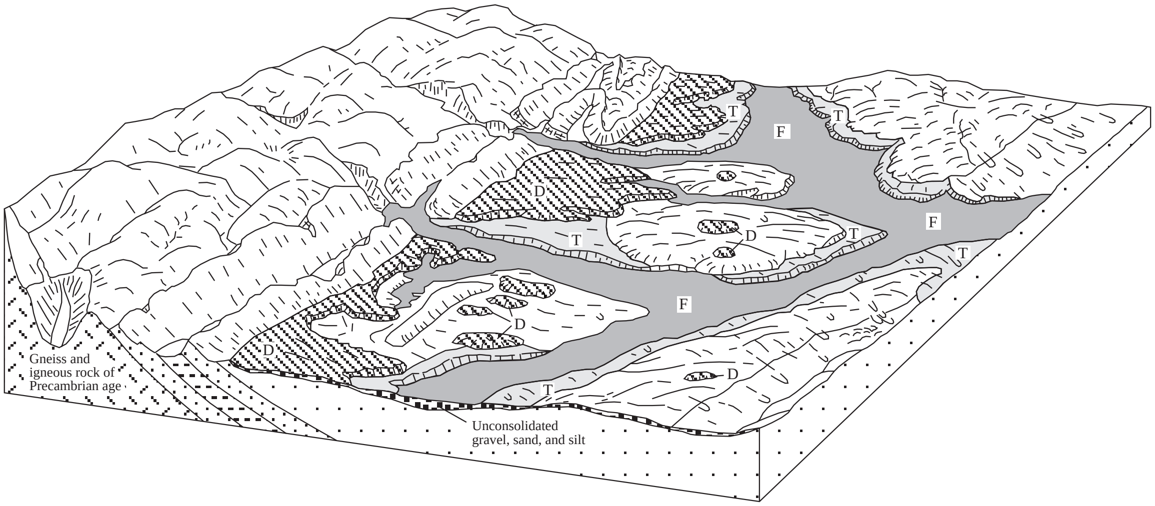


Figure 1. Map showing the South Platte River and tributaries east of the Front Range, Colorado; the locations of

data sources and the cross-sections of figure 3; and the distribution of quartzite in gravel (from Lindsey and others, 2005).

Gravel underlies multiple terrace levels in the valleys of the South Platte River and its tributaries (Fig. 2) (Colton and Fitch, 1974a; Colton, 1978; Schwochow and others, 1974a,b;Trimble and Fitch, 1974; Trimble and Machette, 1979). From highest (oldest) to lowest (youngest), the levels are (1) dissected alluvial fans and terraces (pre-Rocky Flats, Rocky Flats, Verdos, and Slocum) of Pliocene (?) and early and middle Pleistocene age, (2) continuous alluvial terraces (Louviers and Broadway) of late middle and late Pleistocene age, and (3) low terraces and floodplains (Piney Creek and post-Piney Creek) of Holocene age (fig. 2). Dune fields of fine sand, silt and clay cover levels (1) and (2) away from the mountain front. Locally, gravel is produced from each level, but most gravel production is from low terraces and floodplains.



block diagram from E. J. Crosby, 1978

EXPLANATION

AGE	SURFACE FEATURE		STRATIGRAPHIC UNIT
Holocene and Pleistocene		Dune fields	Eolian sand and silt
Holocene	F	Floodplain and low terraces	Post-Piney Creek and Piney Creek Alluvium
Late and Middle Pleistocene	T	Alluvial terraces	Broadway and Louviers Alluvium
Middle and Early Pleistocene, Pliocene (?)	D	Dissected alluvial fans and terraces	Slocum, Verdos, Rocky Flats and pre-Rocky Flats Alluvium

Figure 2. Block diagram showing generalized physiographic and alluvial units of the South Platte River and its tributaries east of the Front Range, Colorado (from Crosby, 1978).

Bedrock claystone of the Upper Cretaceous and Paleocene Denver Formation underlies the gravel fill of the South Platte valley north of Denver. In many of the tributary valleys such as the Cache la Poudre, Late Cretaceous Pierre Shale underlies gravel fill. The bedrock claystone and shale form impermeable seals beneath the gravel aquifer, confining ground water flow to the gravel. After mining gravel, the pit walls can be lined with clay from the underlying formation to create a watertight reservoir. The reservoir, separated from the gravel aquifer by impermeable clay walls, can be used to store water for municipal use.

Where the gravel fill lies on the sandstone aquifers of the Denver Formation (as along Clear Creek) or the Upper Cretaceous Laramie Formation and Fox Hills Sandstone (South Platte

River downstream from Fort Lupton and Cache la Poudre River in the vicinity of Greeley), ground water enters the subsurface of the Denver basin (Robson and others, 1998). Gravel pits that overlie sandstone aquifers may not be suitable for water storage.

Wind-blown deposits of loess (fine sand, silt and clay) overlie gravel of the late Pleistocene Broadway and older terraces in the valleys of the South Platte (fig. 3) and Cache la Poudre Rivers. Along the east side of South Platte valley, loess interfingers with upland dune deposits. In some places, thick wind-blown deposits may preclude gravel mining.

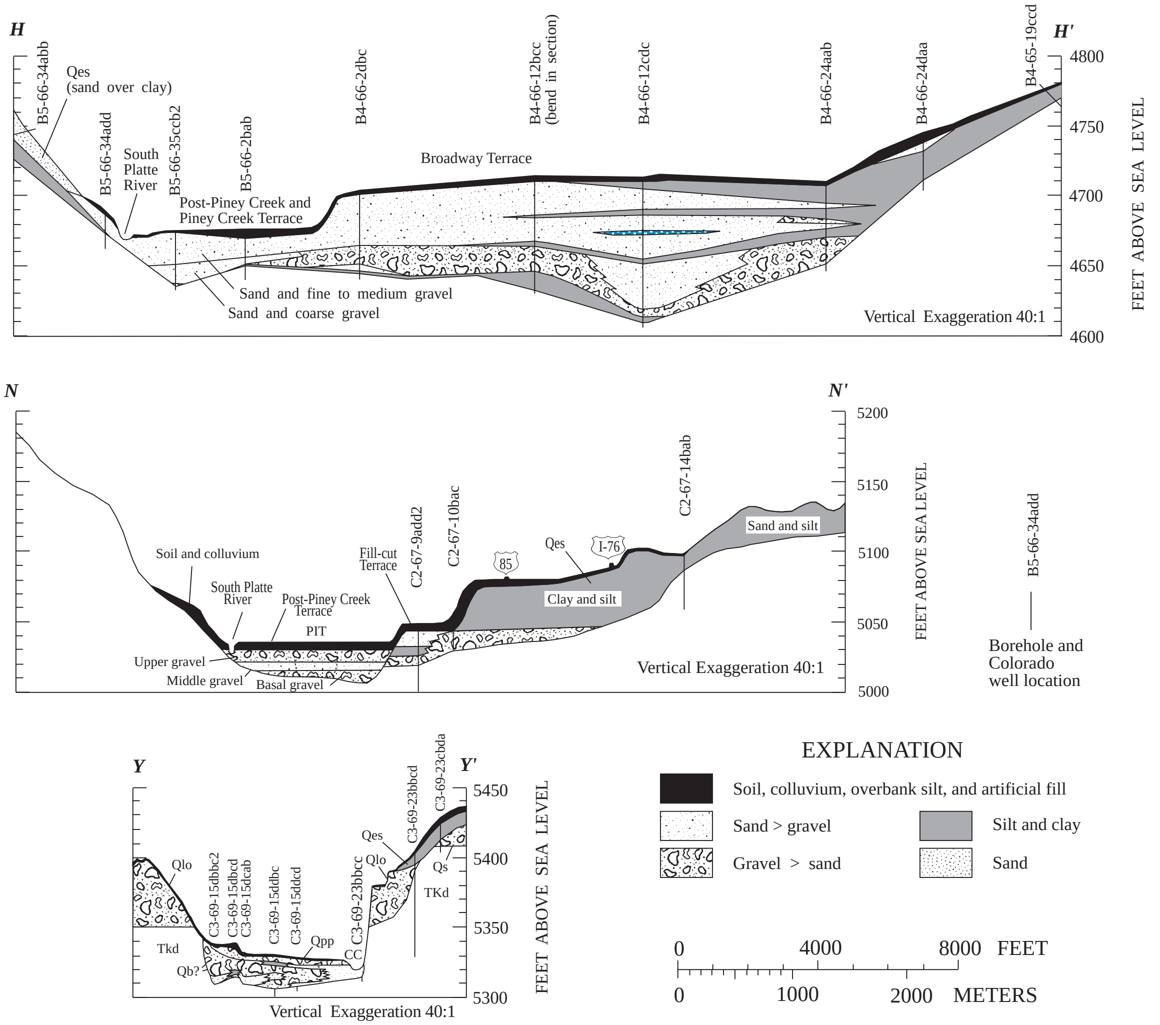


Figure 3. Cross sections showing representative valley-fill stratigraphy in the South Platte River and a tributary (from Lindsey and others, 2005): H-H,' South Platte River between Platteville and Greeley; N-N,' South Platte River between Commerce City and Brighton; and Y-Y,' Clear Creek between Golden and Commerce City. Unit symbols: Qes, Quaternary eolian sand, silt and clay, Qpp, Holocene post-Piney Creek alluvium; Qp, Holocene Piney Creek alluvium; Qb, late Pleistocene Broadway alluvium; Qlo, late middle Pleistocene Louviers alluvium, Qs, middle Pleistocene Slocum alluvium; Tkd, Paleocene and Late Cretaceous Denver Formation. CC, Clear Creek channel. Sections located on figure 1.

THICKNESS, STRATIGRAPHY, AND PARTICLE SIZE

Approximately 20-40 feet of gravel underlies the floodplain and flanking Broadway terrace of the South Platte River valley near Denver (Lindsey and others, 1998; 2005). North of Platteville, where the valley widens and is joined by St. Vrain Creek and the Big and Little Thompson Rivers from the west, the valley fill reaches 100 feet in thickness. Combining the width of the floodplain and the Broadway terrace, the valley ranges from 1-2 miles wide near Denver to as much as 5 miles south of Greeley.

North of Denver the gravel contains three distinct units, each about 5-10 feet in thickness (Fig. 3). The three units differ in coarseness and color and they can be traced as far north as Fort Lupton (Lindsey and others, 1998). The basal gravel is composed of coarse pebble-to-cobble gravel and is interpreted to have been deposited at the end of the late Pleistocene Pinedale glaciation. The middle gravel contains more sand than gravel and is transitional into the lower gravel. The upper gravel, of Holocene age, contains lenses of variable particle size, including pebbles, cobbles, and sand. Overall, however, the upper gravel is coarser-grained than the middle gravel and everywhere it rests on a channeled surface eroded into the middle gravel. The upper gravel is gray in color and appears less-oxidized than the brownish-colored middle and lower units. Locally, the upper gravel contains abundant wood and ancient logjams. Lenses of silty clay, which impede mining, occur locally in the upper and middle units. Downstream from Fort Lupton, the coarse basal gravel occurs sporadically and sand dominates the valley fill.

Gravel fill in major mountain-sourced tributary valleys is generally thinner and the valleys are narrower than the South Platte River valley, but particle size is coarser (Lindsey and others, 2005). Pebbles and cobbles are the dominant particle size; sand occupies spaces between pebbles and forms thin lenses. Detailed sampling of gravel pits in the Cache la Poudre River demonstrated downstream decrease in particle size (Lindsey and Langer, 1998; Langer and Lindsey, 1999), but all gravel in the Poudre valley is sufficiently coarse for commercial mining.

Distinct stratigraphic units can be identified in gravel fill of some tributaries, such as Boulder, Clear, and Turkey Creeks. In these valleys, sand lenses in gravel can be mapped locally using borehole logs (for example, fig. 3, section *Y-Y',* across the valley of Clear Creek). All except the uppermost units are interpreted as late Pleistocene in age, deposited by sediment-rich meltwater at the end of the Pinedale glaciation. In contrast, much of the Cache la Poudre valley contains two widespread gravel units that do not differ significantly in particle size or lithology (Langer and Lindsey, 1999). The units are distinguishable only in pit walls by an erosional boundary and a color change. The lower unit is interpreted to be late Pleistocene in age, whereas the upper unit is Holocene (Lindsey and others, 2005). A corresponding pair of units has been identified in valley fill of St. Vrain Creek ((Madole, 1976)

Terrace deposits of middle Pleistocene age flank valleys of major tributaries such as the Cache la Poudre River, Boulder Creek, and Clear Creek. These deposits consist mostly of coarse pebble and cobble gravel and, although lightly to moderately weathered, are sometimes exploited for aggregate. Other deposits of middle Pleistocene age fill a former channel of the South Platte River east of its present course (Smith and others, 1964). The middle Pleistocene channel of the South Platte extended northeast from Commerce City, then north through Beebe Draw, to join the Cache la Poudre River east of Greeley.

The early Pleistocene Rocky Flats Alluvium is a good example of a mountain-front alluvial-fan deposit (Knepper, 2005; Lindsey and others, 2005). The Rocky Flats fan consists almost entirely of coarse gravel and contains only a few lenses of sand. Gravel thickness reaches 100 feet in buried valleys beneath the Rocky Flats surface, although thickness over buried ridgelines is much less. A second mountain-front fan of early (?) Pleistocene age is partially preserved at Table Mountain, north of Boulder (Madole, in Dethier and others, 2003).

Valley fills of streams that head in the plains generally contain sand but only minor amounts of coarse gravel. Bedrock is commonly friable sandstone and soft claystone; hard bedrock and gravel in Pleistocene and older formations are sparse. However, rhyolite and conglomerate of Oligocene age crop out east and southeast of Denver (Bryant and others, 1981). Northeast of Greeley, gravel composed of igneous and metamorphic pebbles and cobbles fills paleovalleys in both the Miocene Ogalalla Group (Emmett Evanoff, written commun., 2004) and the Pliocene Nusbaum Alluvium (Scott, 1982). Along East Bijou Creek, about 40 miles east of Denver, pebble and cobble gravel composed of granitic rock, quartz, and quartzite has been mapped on terraces of early (?) and middle Pleistocene age (Soister, 1972; Bryant and others, 1981). All of these deposits provide local sources for gravel in plains streams, but their contribution is generally overwhelmed by large amounts of windblown and alluvial sand and silt.

GRAVEL LITHOLOGY, SOURCE, AND WEATHERING

Mountain-sourced streams provide an abundant supply of coarse pebbles and cobbles of granite, pegmatite, gneiss, and quartzite to the South Platte River and its tributaries (Lindsey and others, 2005). Minor lithologies include volcanic porphyry, vein quartz, mafic metamorphic and igneous rocks, and sandstone, but these rocks together generally make up less than 10-20 percent of the total. Abrasion tests (Davenport and Langer, 1998; Lindsey, 2003) show typical Los Angeles (LA) degradation values near 40 for South Platte gravel. Among major gravel lithologies, about 75 percent of LA values are near 30-50 for granite and quartzite and 25-40 for gneiss. Among the minor components, volcanic porphyry and vein quartz are notably durable (LA values near 20 and 33, respectively) and sandstone is soft (75 percent of LA values were 45-75). The LA values for gravel depend upon the exact mixture of these rocks and the degree of weathering.

The principal lithologic variable in gravel of the South Platte drainage system is quartzite (Fig. 1). Quartzite is principally available from the mountain headwaters of Coal Creek, where a distinctive hard, blue-gray metaquartzite is interleaved with Precambrian gneiss (Wells and others, 1964). From early Pleistocene time (and perhaps earlier) the quartzite of Coal Creek has been dispersed by tributary streams into the South Platte River basin (Lindsey and others, 2005). Initially, quartzite was transported easterly onto the Rocky Flats alluvial fan and out to the South Platte via Big Dry Creek. Later, during middle Pleistocene time, Coal Creek beheaded Big Dry Creek at the apex of the fan and quartzite was dispersed northeasterly. The dispersion train of quartzite extends northeast from the head of Coal Creek to the low hills east of the South Platte River, a distance of about 40 miles (Fig. 1). At Rocky Flats, close to the source, quartzite makes up about 50-90 percent of gravel, with granite, gneiss, and pegmatite accounting for much of the remainder. Farther away from the source, quartzite is diluted to less than 15 percent of the gravel.

Cache la Poudre gravel is dominated by granite (25 percent) and its coarse variant, pegmatite (48 percent) (Langer and Lindsey, 1999). Gneiss, vein quartz, and quartzite make up another 5-7 percent each. Quartz plus quartzite increases slightly with downstream distance, from about 5 percent near Fort Collins to about 15 percent near Greeley. This increase is probably the result of the greater hardness and thus, survivability of quartz and quartzite, but the increase is so small that it does not translate into increased gravel quality. About 70-80 percent of all pebbles in Cache la Poudre valley gravel between Fort Collins and Greeley are of satisfactory physical quality for use as aggregate; no downstream change was observed. (The physical quality of individual pebbles was tested by visual inspection and by striking with a hammer.) Slightly more quartz plus quartzite is found in the upper gravel unit, but again this difference does not translate into a difference in physical quality.

Weathering has a profound effect on the quality of gravel in the South Platte River basin. Pebble counts of quartzite-bearing gravel show that the proportion of quartzite plus vein quartz increases with age (Lindsey, 2003) because only the most durable lithologies (mainly quartzite and vein quartz) can be recovered for counting. Other lithologies, such as granite and gneiss, tend to disintegrate to sand and silt during prolonged weathering (Laughon, 1963). In the case of early Pleistocene gravel at Rocky Flats, roughly estimated to be more than a million years old (Dethier and others, 2001), large quantities of sand and silt are produced during mining. This sand and silt is the product of weathered granitic and metamorphic rocks. Similarly, in deeply weathered gravel of middle Pleistocene age a few miles south of Rocky Flats, pebbles and cobbles are weak and friable. Undoubtedly, the presence of weather-resistant quartzite accounts for the quality of aggregate in weathered gravel at Rocky Flats.

Except for gravel containing high proportions of quartzite, the highest-quality gravel of the South Platte River and its tributaries is found beneath terraces of late middle and late Pleistocene age, and beneath Holocene floodplains. Some of these deposits (Louviers) may be as much as 200,000 years old, but many (Broadway and younger) are less than 30,000 years old, the time of the last major glaciation (Madole, 1991; Madole and others, 1998). Such young gravel has not been deeply weathered and its principal components—granite, gneiss, and pegmatite—have not appreciably weakened or disintegrated. Young gravel, which is found in abundance in the South Platte River valley and its major tributaries, is the most widely mined in the Front Range Urban Corridor.

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Cement Plants: A Great Opportunity to Teach People about Minerals.

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ABSTRACT

With the continued expansion of the economy and the rise of California's standard of living, the public is becoming ever more removed from the ultimate source of our society's richness, and the mining community is discovering the challenge of finding ways to educate the public more and more difficult. California's political culture has allowed the development of one of the most regulated industrial environments in the U.S. While cement plants are not as plentiful as, for example construction aggregate plants, they may be still be one of the best ways in which to demonstrate the dependence of our communities on minerals and mining development. Mining representatives that are located in communities with cement plants can take advantage of the opportunity for education of the public that a cement plant offers. This presentation takes a look at the features of a cement plant that can present opportunities to educate the public about the absolute necessity of minerals in their lives.

A cement plant demonstrates mixing and blending of several different minerals in a spectacular, yet accessible way. Everyone can identify with having to combine different ingredients to make something, so introducing the simple chemistry of mixing and blending rock, minerals, and elements is not much of an intellectual stretch. Making cement is a manufacturing process which utilizes the most common minerals in the earth's crust. In addition, cement plants also have a quarry with the attendant drilling, blasting, loading, hauling and crushing, before the material is transferred to the plant. The cement plant demonstrates relatively simple chemistry in which raw calcium carbonate feed from the mine is calcined and then mixed with additive raw materials (silica, alumina, iron) that provide the basic ingredients for cement. The requirement of cooking the raw crushed-to-a-powder feed in a kiln at temperatures of up to 3,000° Fahrenheit can be impressive and offers the opportunity to consider the benefits and drawbacks of various sources of energy.

The opportunity to demonstrate environmentally sensitive operational practices at cement plants includes the discussion of recycling many industrial wastes such as slag, filter cake, and waste tires. Significant reductions in potentially harmful emissions can be achieved by burning waste tires and sewage sludge. Such practices in modern California cement plants can augment the demonstration of successful reclamation practices at the plant and quarry.

INTRODUCTION

With the continued expansion of the economy and the rise of California's standard of living, the public is becoming ever more removed from the ultimate source of our society's richness, and the mining community is discovering the challenge of finding ways to educate the public more and more difficult. Those of us who work in the construction materials environment are daily faced with the astonishment of citizens who profess no knowledge of local mining operations. Inevitably these citizens associate mining with “old timey” guys with long beards and a “trusty” mule to keep them company out in the “boonies”.

California’s political culture has encouraged and allowed the development of one of the most regulated industrial environments in the U.S. This, combined with a general ignorance about the realities of today’s mining environment, presents problems, not only to the ongoing operations of existing mining concerns, but also in the identification and permitting of new mineral resources sites.

While cement plants are not as plentiful as, for example, construction aggregate plants, nevertheless they may still be one of the best ways to demonstrate the dependence of our communities on minerals and mining development. Mining representatives and geologists who are interested in community outreach and are located in communities with cement plants can take advantage of the opportunity for education of the public that a cement plant offers. If you are so fortunate to be located within travel distance of a cement plant, you are afforded an opportunity to educate regular folks about the geology, mining, chemistry, and transportation of the most ubiquitous minerals used by society.

This presentation highlights some of the features of a cement plant that can present opportunities to educate the public about the absolute necessity of minerals in their lives and the basic geological, chemical, environmental and marketing principles that make minerals available to our communities.

THE CEMENT RECIPE

A cement plant demonstrates mixing and blending of several different minerals in a spectacular, yet accessible way. Demonstrating that making cement is a manufacturing process that utilizes the most common and abundant minerals in the earth’s crust is an important concept that can dampen some of the public’s “resource depletion anxiety” fed by an ignorant media and many of our non-governmental organizations. Everyone can identify with having to combine ingredients to make something, so introducing the simple chemistry of mixing and blending rock, minerals, or elements is not too much of an intellectual stretch for most non-mining visitors. A simple cement recipe leads to the introduction of a simplified chemical formula that introduces the basic principles of chemistry. The basic Cement Recipe is as follows (Shumway, 2000):

The CEMENT RECIPE
65% Calcium Carbonate (limestone)
20% Silica (quartzite, sand)
5% Alumina (clay or bauxite)
5% Iron (magnetite)
5% Calcium Sulfate (gypsum)

PROCEDURE:
Mix the Calcium Carbonate, Silica, Alumina and Iron together
Grind to a fine powder
Cook over high heat (about 2600 degrees F) stirring constantly. This will make a hard clinker (should look like uniform balls)

Allow clinker to cool
When the clinker is cool, grind the clinker to a fine powder
Grind up the Calcium Sulfate and add to the Clinker powder
Put the powder into bags for shipping or send to silos for later shipping in bulk
Store in a cool dry place until ready for use
To use: combine with aggregate and water to make concrete

THE QUARRY: the basic raw material

The quarry at a cement plant supplies the largest raw material component by volume. Most non-geologists have no idea why quarries or mines are located where they are. The quarry is the obvious place to begin because not only does a cement plant's quarry have all the attendant drilling, blasting, loading, hauling and crushing before the material is transferred to the plant, but it is an excellent place to demonstrate some of the basic principles of geology, geologic history, mineralogy, and common mining practice.

Discussions at the quarry (or in some cases quarries) may include the very basics such as the differences between rocks and minerals, the origin of the rocks, and what the rocks can tell us about past environments and geologic history of the area. Because a quarry shows the crust in 3 dimensions it affords an opportunity to demonstrate the principles of structure using any folds, faults or unconformities that may be present.

The first stop at the quarry is also first stop in our cement recipe, and an opportunity to introduce some basic chemistry. The plant chemist must be able to blend the limestone raw materials which may include limited content of silica, iron, and even alumina. Most cement plants blend low-grade limestone with high-grade limestone to get to an optimum CaO mix. Often the first blending takes place at the quarry. Each blast is sampled and analyzed to provide the Quarry Manager with basic chemical information with which to blend the low- and high-grade rock to get an optimum mix of calcium carbonate for the cement batch. The basic cement formula is:

$$CaCO_3 + Al_20_3 + Fe_3O_4 + SiO_2 + \text{heat} = \text{Tricalcium silicate (C3S)} + CO_2$$

Actually it is not as simple as the chemical formula listed above because cement is composed of several compounds which, in various ratios, impart qualities to the cement such as sulfate resistance, early strength, late strength, and plasticity. Tricalcium silicate ($3CaOSiO_2$) is only the most common compound; the others include Dicalcium silicate ($2CaOSiO_2$), Tricalcium aluminate ($3CaOAl_2O_3$), and Tetracalcium aluminoferrite ($4CaOAl_2Fe_2O_3$).

The quarry introduces the basic principles of geology and chemistry. The calcium carbonate raw materials from the quarry are mixed with the additive raw materials that provide the silica, alumina and iron; this mix composes the raw feed sent to the kiln.The principles introduced at the quarry are refined and elaborated upon when introducing the additives that provide the rest of the basic ingredients for cement.

THE ADDITIVES: Silica, Alumina, Iron, Recycled Materials

Cement manufacture requires a variety of additives that can be as interesting as the basic raw material, and afford continued discussions of geology and chemistry. If the additives are natural, the locations of the resources, geologic settings, environments of formation, chemical compositions, and any marketing constraints can be emphasized. The costs and logistics of transportation associated with the natural additives may be introduced. The presence of many minerals at the cement plant also affords the opportunity for collecting a suite of minerals (required for example, for the and Boy Scout, Webelos, and Girl Scout Geology merit badges).

Many cement plants in California have opportunities to recycle waste from other industries for use as the additives. The various natural resources that provide the additives for cement manufacture are introduced below.

Alumina

Although some California cement plants use various types of local low alkali clays, the most ubiquitous alumina additive in California is bauxite from Australia or Malaysia. The unique appearance of bauxite (especially the unique appearance of oolitic bauxite) is also an interesting characteristic that can be used to describe the tropical geologic environments in which the mineral bauxite is formed. This can lead to a discussion about why there are few and limited bauxite deposits in the U.S., and why they are located in the southeastern States. Clay or bauxite alumina resources also provide some of the silica necessary for the cement manufacturing process.

Silica

The limestone used to manufacture cement may contain sufficient silica to satisfy the silica requirement. Most California producers, however, add some silica, usually from sources close to the plant. The sources of silica in cement manufacture can vary widely and whatever material additive is used at cement plant can be used to emphasize geologic environment of formation and marketing realities. A plant, for example, that does not need to import silica, or needs only very little silica, can have an significant economic advantage in the reduction of costs required to provide that additive.

Iron

The sources of the iron requirement in California cement manufacture vary from primary magnetite to the recycled tailings from closed iron mining sites. A portion of the iron requirement can also come from the limestone (if a dirty “cement grade” limestone), or from the clay or bauxite alumina source, but cement plants in California import iron for the process. There are only two active iron mining sites in California and the market for the ore is the California cement industry. The geological nature of those iron ore deposits is a great contrast to the geological setting and environment of formation of the carbonate, alumina clays, or siliceous raw materials exposed at the cement plant quarry site(s) or imported from other mining sites. Aside from the different environment of formation, the need for iron in particular provides another opportunity to discuss marketing, limited geological occurrence, and substitutes for additives in the cement manufacturing process.

Recycled Materials

Modern cement plants are becoming recognized as suitable sites for the processing of recycled materials. The elevated temperatures of the kiln have "proven an effective solution for the disposal of waste materials" (Woodbine, 2006). Recycled materials in use at California plants includes diatomaceous filtering media (silica), filter cake from water purifying operations (calcium carbonate and alumina), prills from petroleum cracking (alumina) and dross from aluminum recycling operations (alumina). Foundry sands and brick can provide silica and alumina. Iron resources can be substituted by used abrasive media (silica and iron), mine waste tailings (silica), and steel belted tires.

A plant that processes recycled materials provides an opportunity to discuss the reasons why recycled materials can substitute for natural materials. The opportunity to use substitutes for the additives in cement manufacture can be based upon the location and availability of the raw materials (i.e. urban cement plants have more access to various industrial materials), the availability of tipping fees (i.e. the plant gets paid for taking the materials and the lead agency does not have to place it in a landfill – making the acceptance of some recycled materials economic). It can also be emphasized that the use of many substitutes extends the life of the natural resources.

ENERGY

Energy is the most costly additive in cement manufacture. The requirement of cooking up the raw crushed-to-a-powder feed in a kiln at temperatures of up to 3,000° Fahrenheit offers the opportunity to consider the benefits and drawbacks of various sources of energy. Most cement plants burn coal, oil, or natural gas, causing community concern about the generation of greenhouse gasses. Aside from coal or natural gas, cement plants use various other industrial materials as fuels including tires and sewage sludge. But many other materials can be substituted for the usual energy resources including green waste such as sawdust, woodchips, agricultural waste, and biomass (discussed below). Waste such as oil impregnated sawdust, chemical residues, and other organic materials designated as "hazardous" causes public concern (often unfounded) and requires special permits that are difficult to attain.

The use of recycled materials can be an effective starting point for discussions about the need for energy in producing the materials that our communities need and the benefits (and liabilities) of using various recycled materials. Many of the various materials used as substitutes for coal or natural gas have positive environmental impacts on the gasses that emit from a cement manufacturing plant, and are proving to be an effective environmental solution to disposing of some waste materials. For example a tire has the energy equivalent of 1.2 times that of coal, by weight (and the steel belts provide some of the iron requirement). Both tires and sewage sludge help reduce nitrous oxide emissions, which are a major component of smog.

DISCUSSION: THE LESSONS

The cement plant is a great place to teach visitors about the basics of geology, earth science, chemistry, marketing, recycling and environmental stewardship.

- Geology: The cement plant quarry or quarries can be used as effective geology labs. A quarry or mine allows students (the non-geological and non-technical public) to observe the crust in three dimensions and observe first hand the basic principles of, stratigraphy, structure, and rock types; principles that are also important to cement manufacture. Local and regional geologic history and environments of ore formation can also be emphasized. These discussions can be helpful at answering the too common question, “Why does the mine have to be here?”

- Chemistry: A discussion of basic chemistry begins at the quarry with the discussion of blending the raw materials in the quarry, based on the chemical analysis from a blast, to attain the desired tricalcium silicate (C3S) target. Manufacturing cement is basically mixing several ingredients to get a product and can be modeled using several chemical formulas. The introduction of the basic chemistry of cement answers the question of why a variety of raw materials are required for cement manufacture. Chemistry also drives the use of recycled materials as substitutes for the natural raw materials.

- Mining: Any visit to a mining site allows an opportunity to discuss mining plans, common mining practice, the use of mining equipment, the effectiveness of drilling and blasting as reliable mining practice. Any mystique of the “old timey” miner can be easily replaced by seeing modern miners working large machinery in a modern mine setting.

- Transportation and Marketing: The location of a cement plant often determines the markets that can be served economically. Because transportation costs affect the costs of additives, the plant location can determine the types of additives and the potential of using recycled materials as additive substitutes, as well as the overall operating costs of cement manufacture. As in any competitive market, lowering costs while producing a material that meets rigorous specifications can have a significant economic advantage.

- Recycling: Cement plants are efficient places to recycle various waste materials. Discussing the use of substitutes for the additives and energy raw materials in cement manufacture revisits the discussions of chemistry and how the various materials can satisfy the various chemical requirements. It also addresses the issues of cost of additives, how recyclables are competitive because of tipping fees, proximity, and because their use extends the life of natural mined additive materials (Shumway, 1999).

- Environment: A visit to mine site usually includes a tour of the reclaimed habitat sites, the nursery, or the shade house. Any mine visit should also emphasize the fact that no mine operates without community consent and oversight. A visit from the community is an opportunity to demonstrate good mining and environmental stewardship.

- The Products: Everyone can identify with the principal product of cement—concrete! If the cement plant visit can be combined with a visit a nearby aggregate facility, or if the connection can be made to any community infrastructure, the story of concrete is complete. The obvious associations to be made by the non-geologist and the non-miner can be a powerful connection to the necessity of insuring a continued supply of minerals to our communities.

CONCLUSION

Cement plants produce a product with which most people can identify. By highlighting the energy requirements, raw materials, and the many substitutes for those raw materials, the geologist can introduce a visitor to the basic principles of geology, chemistry, mining and the logistics of transportation, marketing, recycling and environmental stewardship. The geologist who uses the local cement plant as an educational tool can help to educate a largely unaware public about the absolute reliance of our communities on minerals. Cultivate a relationship with the local cement producer and learn to use your local cement plant as an educational tool.

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Geology of the Dolomitic Marble of Lusaka, Zambia, Southern Africa

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ABSTRACT

Zambia is endowed with abundant industrial mineral resources and among these are carbonate rocks (limestone, marble and dolostone), phosphate rock (e.g. syenites and carbonatites), graphite, clay, gypsum, sand and gravel, talc, feldspar, micas, gemstones, and granite. These industrial minerals and rocks occur throughout the stratigraphic sequence from Archean to Recent.

In this paper, however, the focus is on the geology of the dolomitic marble underlying most of Lusaka, the Capital City of Zambia, which has been and continues to be a source of among others: (i) aggregate for the construction industry, (ii) agricultural lime, (iii) chicken stock feed, (iv) lime cement production (v) flat stone for facing drainages, parking lots and wall fences, (vi) dimension stone, and (vii) tombstones. The marble is also a major aquifer, a source of groundwater for the city of Lusaka.

The dolomitic marble forms part of the Cheta Formation, which is of Neoproterozoic age and comprises metasiliclastic and metacarbonate rocks. The marble is banded with bands varying in colour from grey through white to pink. The banding trends nearly WNW-ESE the typical structural trend of the Neoproterozoic Zambezi Fold and Thrust Belt. The banding is a result of deformation, which could be of several episodes but the nearly N-S directed one is predominant and probably a result of the last deformation phase. The dolomitic marble comprises calcite, dolomite, rhodochrosite, quartz, mica (phlogopite), amphiboles (e.g. tremolite), forsterite and talc. The grey dolomitic marble bands have been related to an impure limestone precursor, the white marble bands enriched in calcite and dolomite, to a pure limestone protolith, and the pink marble bands, pink due to the presence of rhodochrosite (a manganese carbonate) in a pure limestone protolith infiltrated by a manganese-bearing fluid. The marble has been metamorphosed to amphibolite facies, which probably, was later down-graded to greenschist facies.

In terms of origin, the dolomitic marble is thought to be of marine origin based mainly on the carbon stable isotopic composition determined on carbonate rocks of similar age in Kabwe area (average $\delta^{13}C$ values of +2.89‰) and in Mumbwa area (range $\delta^{13}C$ values of -2.90 to +6.30‰). This suggests that the dolomitic marble was deposited originally as part of an inorganic carbonate sediment sequence (infiltrated at some stratigraphic positions by a manganese-bearing fluid) in an intra-continental rift marine basin, which later closed to form the Zambezi Belt.

INTRODUCTION

Zambia is endowed with abundant industrial mineral resources and among these are carbonate rocks (e.g. limestone, marble and dolostone), phosphate rock (e.g. syenites and carbonatites), graphite, clay, gypsum, sand and gravel, talc, feldspar, micas, gemstones, and granite. These industrial minerals and rocks occur throughout the stratigraphic sequence from Archean to Recent and also throughout the country. This paper focuses on the geology of the dolomitic marble, underlying most of the city of Lusaka, what it is being exploited for, and some of the negative impacts of its exploitation.

Lusaka, with a population of about 2 million people and growing, is located in central Zambia (fig. 1) and bounded by latitudes 15°10' and 15°50'S and longitudes 27°45' and 28°30'E. The city has, over four decades, grown significantly in population from 123,000 in 1963 (Mulenga, 2003) to nearly 2,000,000 today. This growth has been attributed to the rural-urban migration of people in search of a better life, natural increase (high birth rate) and extension of the city boundaries (Mulenga, 2003). It is estimated, for example, that 40% of the nearly 11 million people in Zambia live in urban areas. This growth in population has, however, not been matched by development in infrastructure (e.g. housing) and the result has been a growth in unplanned settlements with improper and inadequate water supply and sanitation facilities. The need for more housing units alone has led to the growth of both the formal and informal sectors in the exploitation of the carbonate rocks in and around Lusaka mainly for production of cement and aggregate. In fact, since the commencement of the privatization programme in 1990s by the Zambian Government, the informal sector has grown tremendously as people, being retrenched as a result of either restructuring of parastatal organisations or the privatization programme, try to seek other ways to survive.

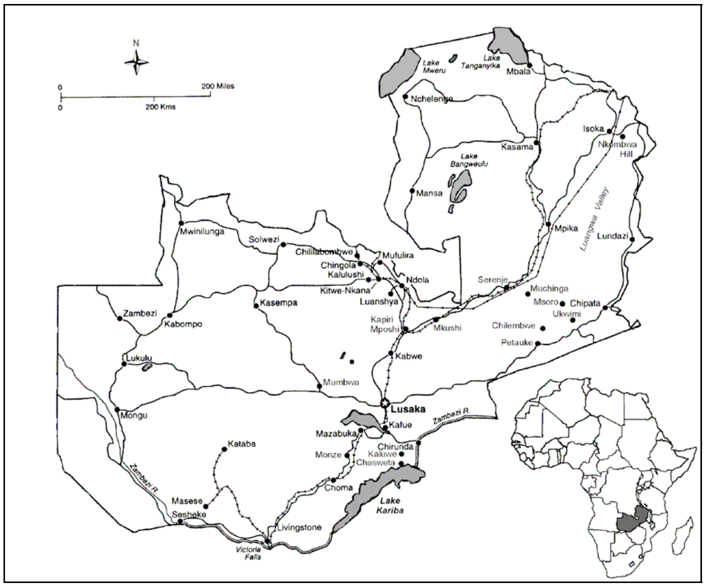

Figure 1. Location map of Zambia and the city of Lusaka.

REGIONAL TECTONIC AND GEOLOGICAL SETTING

Tectonically, the Lusaka area is set within the WNW-ESE-trending Neoproterozoic Zambezi Fold and Thrust Belt, which stretches from central Zambia into northern Zimbabwe where it is believed to merge with the N-S trending Mozambique Belt (figs. 2 and 3). The Zambezi Belt is, in fact, part of the Neoproterozoic-early Paleozoic system of orogenic belts in central and southern Africa that includes the Damara and Mozambique belts (e.g. Dirks et al., 1999; Porada and Berhorst, 2000; Katongo et al, 2004) (fig. 2). The Damara-Lufilian-Zambezi belt system is probably a result of a closure of a large rift basin between the Congo and Kalahari cratons (fig. 2). Within Zambia, the Zambezi Belt comprises wide zones of remobilized crystalline basement overlain unconformably by a sequence of supracrustal rocks (e.g. Hanson et al., 1988b; Wilson et al., 1993). The nature of the contact between the basement and the supracrustals is believed to be a re-tectonized unconformity (Johnson et al., 2006).

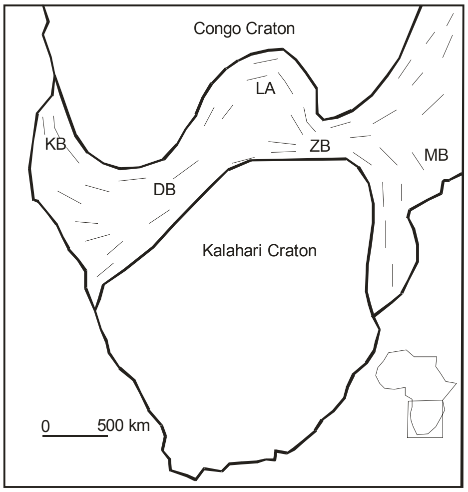

Figure 2. Tectonic map of southern Africa showing the main cratonic units and Neoproterozoic Belts. DB – Damara Belt, KB – Kibaran Belt, LA – Lufilian Arc, MB – Mozambique Belt and ZB – Zambezi Belt.

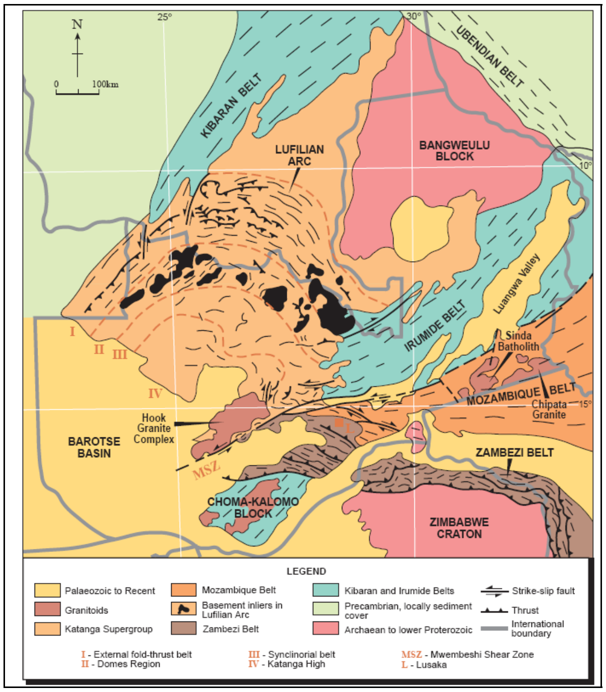

Figure 3. Regional tectonic and geological map of Zambia showing position of the Zambezi Belt in relation to other Neoproterozoic-early Paleozoic orogenic belts (from Porada, 1989).

The basement is composed of two gneiss units, the Mpande Gneiss and Ngoma Gneiss, which form terranes in the central parts of the Zambezi Belt. The ca 1100 Ma Mpande Gneiss is a megacrystic, K-feldspar- and biotite-bearing augen gneiss intruded by a small lensoidal Munali Hills Granite (Smith, 1963; Hanson et al., 1993) dated recently at 1090 Ma by Katongo et al. (2004). The Zambezi supracrustal sequence, believed to have been deposited in a continental rift to oceanic setting along the southern margin of the Congo Craton, comprises a metasedimentary package of clastics and carbonates with minor volcanics and lavas (Johnson et al., 2006).

Using white schists, associated gedrite-cordierite-kyanite gneisses and garnet-staurolite-kyanite schists, John et al. (2004) estimated peak metamorphic conditions within the Zambezi Belt to be about 700±25^{o}C at 10±1 kbar equivalent to high-pressure amphibolite facies conditions interpreted to be a result of crustal thickening. The white schist formation has been related to the final continental collision between the Congo and Kalahari cratons at about 530 Ma during the assembly of Gondwana following the ocean basin subduction and eclogite metamorphism at about 600 Ma (John et al., 2003). According to Porada and Berhorst (2000), the Lufilian Arc-northern Zambezi Belt basin started developing around 880 Ma. The widespread granites and volcanic rocks with ages ranging from 880 to 840 Ma within the Lufilian Arc-Zambezi Belt are interpreted as indicators of incipient extension (Porada and Berhorst, 2000).

In the Lusaka area, the base of the suprucrustal sequence is represented by the Kafue Rhyolite Formation (KRF), a 2.5 km sequence of deformed, variably –metamorphosed rhyodacite flows and tuffs with subordinate rhyolite, tuffaceous sediments, agglomerates and extremely rare, thin mafic horizons (Smith, 1963); Mallik, 1966). The KRF is overlain by the Nazingwe Formation (NF), a thin sequence of tuffaceous semi-pelites with intercalated acid horizons. The KRF and NF pass upwards into the Mulola Formation (MF) of quartzites (Mallik, 1966). The MF is overlain by kyanite-bearing and biotite-rich schists and semi-pelites of the Chipongwe Formation (CF), which in turn is overlain by the Cheta Formation consisting of dolomitic marbles. The Cheta Formation is intruded by abundant gabbroic and ultramafic blocks with N-MORB chemistries (John et al., 2004).

Although no stable isotope studies of the Lusaka dolomitic marble have been done to determine the origin of these carbonates, those of similar age in Kabwe and Mumbwa areas of central Zambia have been interpreted to be of marine origin based of carbon isotopic data. $\delta^{13}C$ values for the Kabwe carbonates average +2.89‰ (Kamona, 1993) and for the Mumbwa carbonates range from -2.90 to +6.30‰ (Sikazwe, 2001). These carbonates are considered to be platform carbonates that got deposited together with siliclastic sediments in the Damara-Lufilian-Zambezi rift basin around 880 Ma.

GEOLOGY OF THE LUSAKA DOLOMITIC MARBLE

Fig. 4 summarizes the local distribution of rocks underlying the Lusaka City with the base being marked by the Matero quartzites, which pass upwards into the Ridgeway schists, the Lusaka dolomitic marbles and subsequently into Quartenary alluvial deposits (De Waele and Follesa, 2003 and contained references). The sequence contains gabbros, metagabbros and eclogites. Eclogites have been interpreted to represent former oceanic crust that subducted to a depth of about 90 km, while the associated gabbros and metagabbros either subducted to a shallower depth or survived the subduction (John et al., 2003).

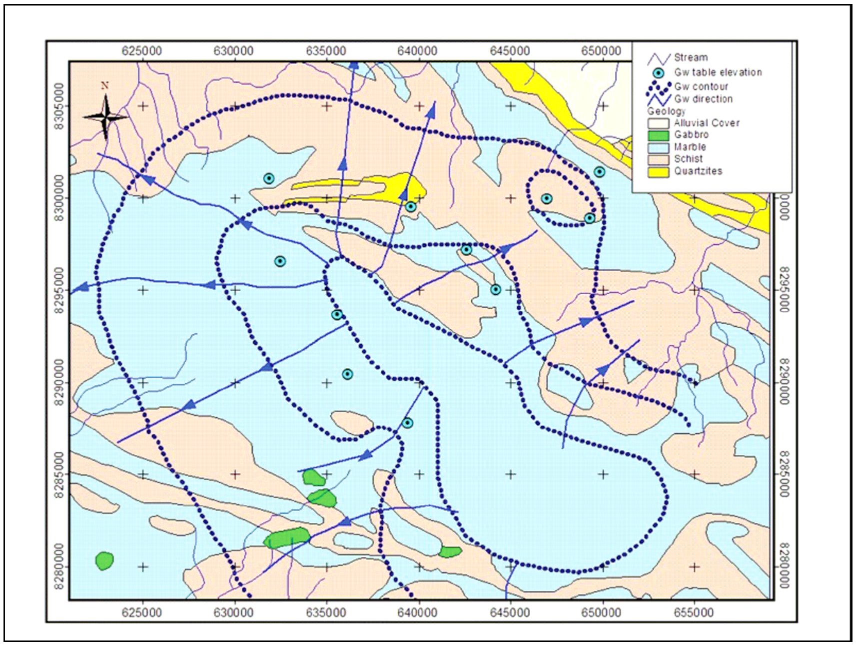

Figure 4. Geological map of Lusaka City showing the groundwater flow directions (from Nkhuwa, 2000).

The Matero quartzites and Ridgeway schists, which outcrop mainly to the north and less so to the south of Lusaka City (fig. 4), are part of semi-pelites of the Neoproterozoic Zambezi Belt suprucrustal sequence described by Hanson et al. (1994). The two lithologies have a nearly NW-SE trending fabric defined by stretched quartz and micas with a preferred orientation. The Lusaka dolomitic marbles, outcropping mostly in the central and southern parts of the city, vary in colour from grey through white to pink, have NW-SE trending bands, are highly crystalline and coarse-grained. The three lithologies (Matero quartzites, Ridgeway schists and Lusaka dolomitic marbles) together constitute the metasediments and metacarbonates of the Cheta Formation. The Lusaka dolomitic marbles comprise mainly calcite, dolomite, rhodochrosite (a manganese carbonate), and minor quartz, mica (phlogopite), amphiboles (e.g. tremolite), forsterite and talc. In some cases so much talc has formed from the Lusaka dolomitic marble that talc deposits have resulted.

The grey dolomitic marble bands have been related to an impure limestone precursor, the white marble bands, enriched in calcite and/or dolomite, to a pure limestone protolith and the pink marble bands due to the presence of rhodochrosite in a pure limestone protolith infiltrated by a manganese-bearing fluid. The banding is a result of deformation, which could be of several episodes but the nearly N-S directed one is predominant and probably as a result of the last deformation phase. This deformation did not only produce the banding but also fractures, joints (parallel, perpendicular and oblique to banding), faults and shear zones.

The marbles have been metamorphosed to amphibolite facies, which was probably later down-graded to greenschist facies. In Mumbwa area, minerals such as forsterite, phlogopite, tremolite, dolomite and calcite where identified in the marbles of similar age and garnet, biotite, muscovite, tourmaline, chlorite, plagioclase in the stratigraphically lower placed gneisses (Sikazwe, 2001) indicating an amphibolite grade metamorphism that may even have retrograded to greenschist facies.

Three holes drilled up to about 100 m (fig. 5) show that the Lusaka dolomitic marbles are not only variably coloured but also weathered in places and have cavities developed in others due to dissolution of the carbonate rocks. The dissolution of the marble has led to the development of karst features and a karst topography (e.g. fig. 6), which are common in Lusaka. Dissolution cavities developed in the marbles coupled with fractures have contributed to the Lusaka dolomitic marble being a major aquifer providing about 70% of water supply to the city (De Waele et al., 2004).

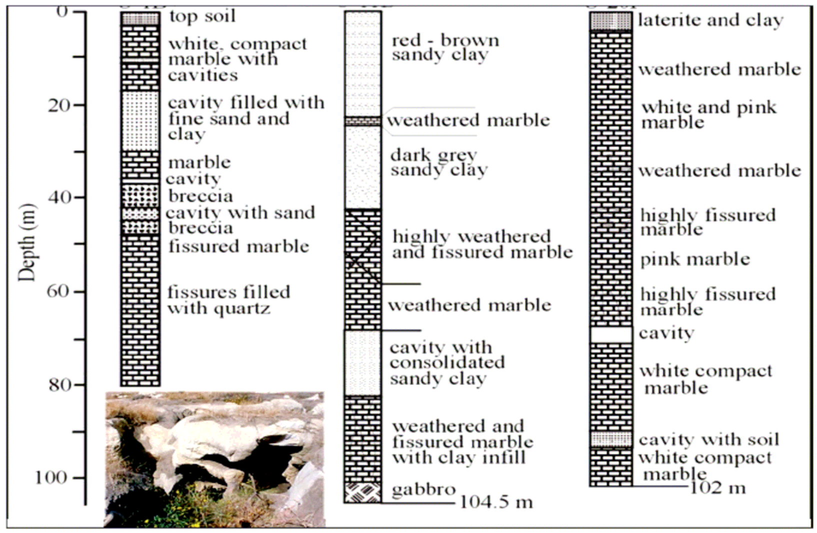

Figure 5. The local stratigraphy of Lusaka dolomitic marble (from Nkhuwa, 2000).

Although we do not know the actual resource of the marbles in and around the city of Lusaka, we can still conclude, from the surface exposure of the Lusaka dolomitic marble and the three holes drilled to an average depth of about 100 m (fig. 5), that the resource is vast. Using a minimum depth of 0.1 km and an outcropping surface area of 1,600 km^2 reported by De Waele and Follesa (2003) a rough and minimum estimate of 160 km^3 volume of the marble can be assumed. This assumed vastness of the resource can be demonstrated by how long it has been exploited. For example, United Quarries Ltd has been producing dolomitic marble aggregate from its two quarries in Lusaka since 1965, Chilanga Cement Ltd has been exploiting the marble for its cement production since 1949.

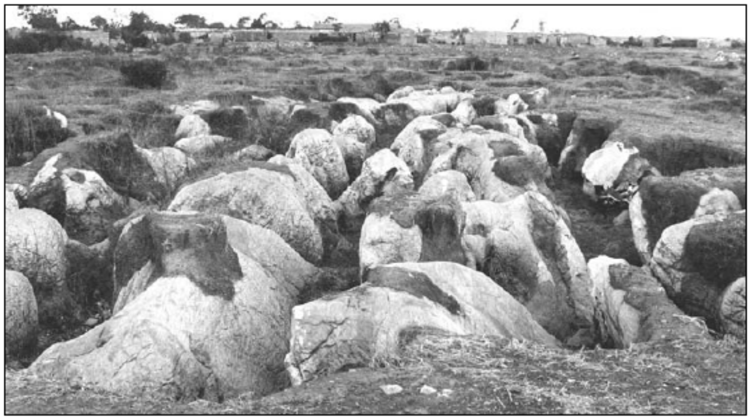

Figure 6. A karstic topography developed over the Lusaka dolomitic marble (from De Waele and Follesa, 2003).

DOLOMITIC MARBLE PRODUCTION AND USES

Most of the production of limestone, limestone products (lime and cement) and marble is concentrated in the Lusaka (Lusaka Province), and Ndola (Copperbelt Province). Small amounts are also produced in Mkushi (Central Province), Mazabuka (Southern Province) and Solwezi (Northwestern Province). The Lusaka and Copperbelt areas, coincidentally, are also the most industrialized and urbanized in Zambia and hence the high demand for the said products. It should be pointed out here that limestone is being used in a very loose sense as most of the carbonate rocks in Zambia are of Precambrian age and as such are highly crystalline qualifying them to be called marble.

Table 1 and fig. 7 show the national production figures of crushed limestone, hydraulic cement, limestone products (quick lime and hydrated lime), limestone (cement & lime) and marble for nearly a decade. This table, however, does not include production from the informal sector i.e. artisanal producers who are not normally captured statistically. Artisanal producers became very active during the decade due mainly to loss of employment as a result of the privatization process implemented after 1990 and the boom in the construction of houses that created demand especially for crushed aggregate and concrete blocks. The table does not equally show all the various products that the limestone and marble are produced for in the country. For marble we can assume that the production figures are for dimension stone and related products.

The general picture though is that limestone (cement & lime) production in Zambia declined from nearly 950,000 mt in 1990 to just above 700,000 mt in 1994 and thereafter increased 800,000 mt in 1995 and leveled off until 1998 when it dropped to just below 100,000 mt in 2001 (fig. 7).

Table 1. Production levels of limestone, limestone products and marble in Zambia between 1990 and 2001 (all production figures are in metric tones – mt; Source: Coackley, 1999 & 2003; and Chilanga Cement, 2005)

Mineral Commodity	Limestone	Limestone	Cement	Quick lime	Hydrated lime	Marble
Year	crushed aggregate	(cement & lime)	hydraulic			
1990	772000	930000	437000	199508	14292	0
1991	739000	810000	367000	199508	14292	0
1992	680000	800000	347000	171267	12517	195
1993	632000	770000	310000	193224	21306	1582
1994	668000	710000	280000	205549	15668	322
1995	700000	800000	312000	194508	16365	89.5
1996	700000	800000	384000	215246	13848	0
1997	700000	800000	384000	173707	9632	207.4
1998	700000	800000	351000	157758	16601	0
1999	460000	188000	300000	107498	11229	0
2000	437000	177000	380000	70818	8282	0
2001	450000	61000	215000	106479	11068	0

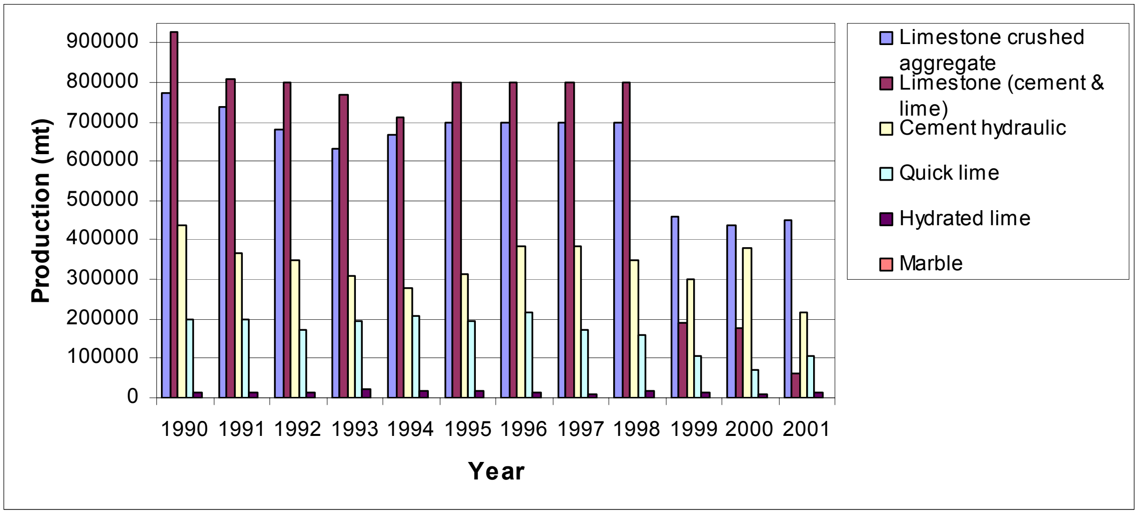

Figure 7.1. Bar graph showing the production of limestone, limestone products and marble in Zambia between 1990 and 2001.

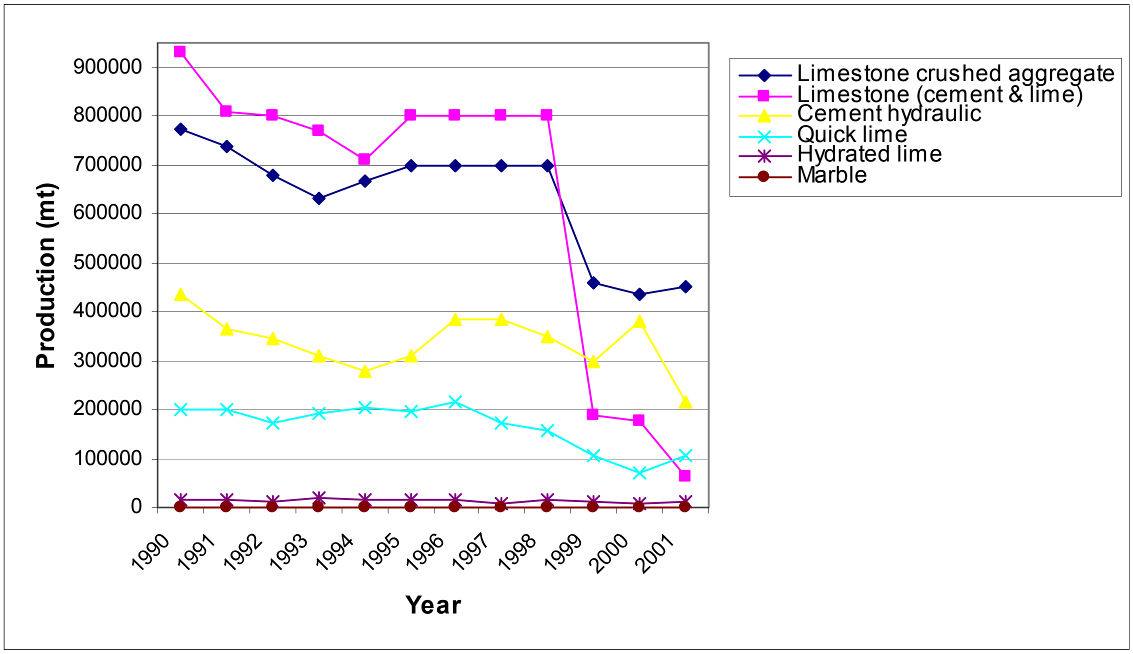

Figure 7.2. Graph showing the production behavior of limestone, limestone products and marble in Zambia between 1990 and 2001.

A similar picture can be said for crushed limestone production, which dropped from nearly 800000 mt in 1990 to just about 650000 mt in 1993 followed by an increase to 700,000 mt in 1995 leveling off until 1998 when it dropped again to about 450,000 mt in 2001 (fig. 7).

Hydraulic cement production was just about 450,000 mt in 1990 but dropped to below 300,000 mt in 1994 and thereafter increased to a peak of just below 400,000 mt in 1996 before dropping again to 300,000 mt in 1999 (fig. 7). The production of hydraulic cement increased again to just below 400,000 mt in 2000 before dropping to 200,000 mt in 2001.

The production of quick lime was steady at nearly 200,000 mt until 1996 when it declined to below 200,000 mt reaching a low of nearly 70,000 mt in 2000 before increasing to about 100,000 mt in 2001 (fig. 7). The production of hydrated lime remained at below 100,000 mt for the whole decade.

The production of marble peaked at nearly 1,600 mt in 1993 before declining steadily (table 1 and fig. 7).

Chilanga Cement exploits marble from which it produces on average about 400,000 mt of cement per year particularly between 1999 and 2005 (Chilanga Cement Plc., 2005). In the same period, production increased from 331,000 mt to 571,000 mt. The cement production is set to double to about 1 million mt in 2008 when Chilanga Cement commissions another cement plant. Chilanga Cement also produces about 440,000 mt of clincker. United Quarries, a company based in Lusaka, produces 80,000 mt of dolomitic marble aggregate per year from its two quarries. United Quarries produces several products and these include aggregate of different particle size (>40, 20, 10, and 5 mm), quarry dust B (mixture of laterite and rock fragments), quarry dust A (rock particles of size <5 mm), concrete blocks of different sizes (4, 6 and 8"), pavers, kerbstone, breeze blocks, and bricks. The >40 mm aggregate is sold to clients for use mainly in constructing sock ways, drainages and wall fences. The quarry dust B is used as a substitute for river sand for constructing foundation slabs. Quarry dust A is a good substitute for building sand. The 5 mm aggregate and quarry dust A are used in the production of concrete blocks, pavers, kerbstones, bricks and breeze blocks.

The various uses that the Lusaka dolomitic marble is being exploited for include in decreasing order of importance: (i) lime for cement production, (ii) aggregate (fig. 8) for construction of engineering structures, (iii) crushed stone dust for railway ballast, the production of concrete blocks and pavement bricks, (iv) lime for agricultural purposes and water treatment, (v) dimension stone (fig. 9) from which floor and wall facing tiles and tombstones are produced, (vi) flat stone (fig. 10) used in facing of wall fences, floors in houses, drainages and car park areas, and (vi) calcium carbonate powder for stock feed especially in the raring of egg-producing chickens.

Figure 8. Aggregate produced by mainly women (a) and children (b) artisanal miners from the dolomitic marble in Lusaka for construction purposes (c).

Figure 9. Photograph of a dimension marble mining site west of Lusaka.

Figure 10. Flat stone exploited from Lusaka dolomitic marble for facing.

NEGATIVE ENVIRONMENTAL AND HEALTH IMPACTS OF EXPLOITING THE DOLOMITIC MARBLE

The exploitation of carbonate rocks in and around Lusaka for whatever purpose by both the formal and informal sectors has led to various negative environmental and health impacts some of which are highlighted in this paper. The environmental impacts include: (i) land degradation, (ii) groundwater pollution, (iii) air pollution, and (iv) noise pollution. Health impacts are: (i) malaria, (ii) cholera and dysentery, (iii) respiratory problems and (iv) death.

Both formal and informal sectors upon removal of the marble from the ground leave behind holes in the ground (figs. 11 and 12) that are never reclaimed probably due to the cost involved and/or lack of enforcement of environmental laws. These holes degrade the land both in terms of value and beauty. It is not only the value of the land that is affected but such holes also increase the cost of building as the holes have to be buried before construction. When stagnant water accumulates in such holes (figs. 11 and 12) they act as breeding grounds for mosquitoes, which are vectors for malaria parasites. The prevalence of malaria, reported to be 1 in 5 out-patients in Lusaka (Banda, 1995), is more common to peri-urban/ inter city shanties than to urban areas because peri-urban areas and inner city shanties have relatively higher numbers of breeding sites most of which are as a result of holes left behind by quarrying. In general, Zambia experiences 4.8 million malaria cases per year resulting in 50,000 deaths (www.kungsholmensgymnasium.stockholm.se/pdfdoc/ malariabyhannahlindberg.pdf) and causes 40% of infant deaths.

Figure 11. A dolomitic marble quarry filled with water and near an unplanned settlement in Lusaka. This quarry was operated by a large company (Crushed Stone Sales Ltd) before being abandoned.

Figure 12. Holes left behind by exploitation of the Lusaka dolomitic marble by the artisanal miners. These act as sites for malaria parasite breeding.

The holes are also used to dump mixed solid waste and sometimes are used as toilets. A survey around Lusaka by the author in 2004 revealed that used quarries, particularly those close to densely populated townships, had a lot of human excreta. The 2 million people of Lusaka generate about 1,100 mt of waste per day (i.e. 400,000 mt per year) and of this only 10% is properly disposed (De Waele and Follesa, 2003). In the rain seasons, the interaction with this waste and excreta and promotes conditions conducive for cholera and dysentery, which in Lusaka lead to a number of deaths each year. Furthermore, because the water table for Lusaka is relatively shallow (as shallow as 2-25 m in certain areas of Lusaka (e.g. Nkhuwa, 2000), holes, in which water has interacted with waste and/or human excreta, act as conduits to pollute groundwater resources for Lusaka. In fact, De Waele and Follesa (2003) have reported nitrate-nitrogen concentration range of 15-40 mg/l (exceeding the WHO limit of 10 mg/l) in water samples taken directly from the Lusaka dolomitic marble aquifer and relate this to pollution caused by decomposing organic matter derived partly from the uncontrolled waste dumping.

The same holes also not only shelter thieves and their stolen merchandise but some of them have been death traps for people leaving in densely populated areas. Death traps in the sense that people, particularly those coming from drinking sprees, have fallen into water bodies, formed as a result of quarries left un-buried, and drowned year after year.

The exploitation of marble by the formal sector requires drilling and use of explosives. Both activities lead to the production of dust and noise. Dust generation generally leads to air pollution that may be associated to some of the respiratory problems reported in some of the communities surrounding the quarries and among employees. Drilling and the use of explosives also generate noise, which has been reported by communities around quarries to be a disturbance. Furthermore, explosives produce vibrations, which have been linked to the development of cracks in engineering structures around quarries in and around Lusaka.

The informal sector miners (arstisans) also degrade the land though on a smaller scale by leaving holes in the ground and similar environmental and health impacts results. These artisans in addition burn car tyres to heat the rocks for them to crack easily and smoke produced from this process is a health hazard both for the miners and communities around. A study by Mushingeh et al. (2002) reveals, as common-very common, the following health problems particularly among children involved in quarrying and stone breaking: headaches, chest pains, sore eyes, injury to fingers/bruises, coughing and sneezing, fatigue, painful/swollen legs, sore necks, and painful ribs. In addition, these children either do not go to or have dropped out of school or they simply do not have the time to attend school.

TALC

In some cases these marbles have been found to contain talc in amounts constituting a deposit. The talc deposit in Lusaka area associated with the dolomitic marbles may have resulted from the transformation of carbonates (dolomite and magnesite) in the presence of silica. The carbonates fix in-situ the magnesium needed to form the mineral whereas the silica is provided by hydro-thermal circulation. Tectonics plays a major role in the genesis of a talc deposit (fig. 13). It enables hydro-thermal fluids to penetrate the rock, creating a micro-permeability that facilitates reactions in the mass. We know that the Lusaka marbles together with other rock units within the Zambezi belt supracrustal sequence are complexly deformed and metamorphosed to amphibolite facies, which latter was downgraded to greenschist facies. Some of the structures observed in the Lusaka marbles include banding of similar trend to foliation in the older schists and quartzites, fractures (in some cases orthogonal joints), shears, and faults. The fractures, shears and faults provided a larger surface area for the marbles to react with hydrothermal and even cold fluids. The cold fluids, which may have percolated downwards through fractures, caused the chemical weathering observed in the Lusaka marbles through karstic features some of which extend to a depth of 100 m.

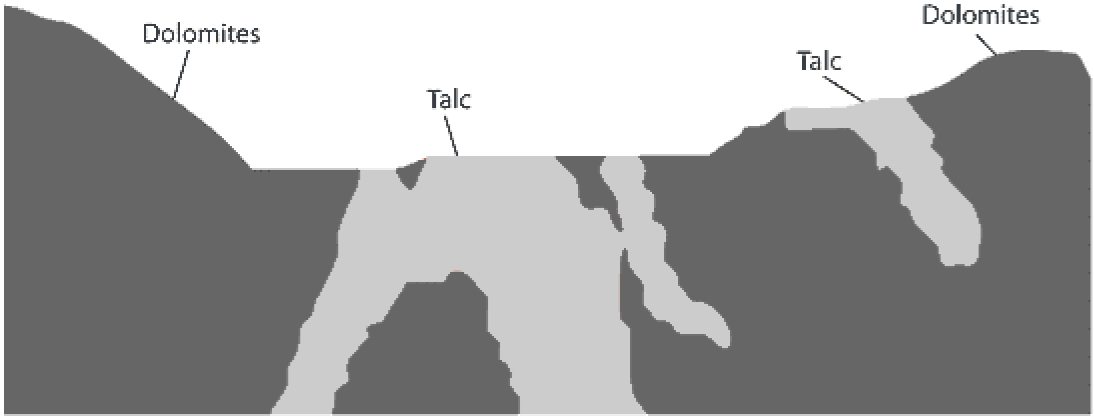

Figure 13. An example of a talc deposit derived from magnesium carbonate rocks e.g. Yellowstone mine in Montana - US (from www.luzenac.com).

SUMMARY

The carbonate rocks in and around Lusaka are of Precambrian age and as such are strictly speaking are crystalline dolomitic limestones or dolomitic marbles. These marbles are coarse-grained, vary in colour from grey through white to pink, banded and contain mainly calcite, dolomite, and rhodochrosite. Rhodochrosite, because of its Mn content, makes the marbles pink.

The Lusaka dolomitic marbles exploited by the formal sector are for lime for cement production, agricultural purposes and aggregates for construction and dimension stone. The informal sector mines the marbles mainly for aggregate and facing of walls. In the process of exploiting the marbles environmental and health impacts results and the main ones are: (i) land degradation, (ii) (ii) groundwater pollution, (iii) air pollution, and (iv) noise pollution. Health impacts are: (i) malaria, (ii) cholera and dysentery, (iii) respiratory problems and (iv) death.

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The Aggregate Potential of Byproducts Generated by Minnesota's Taconite Mining Industry: A Summary of Current Research

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ABSTRACT

Every year, Minnesota's taconite mining industry generates over 125 million tons of mining and processing byproducts, a figure that is more than double the entire state's annual aggregate usage. Since the year 2000, the Natural Resources Research Institute (NRRI), University of Minnesota Duluth, has been investigating how these vast quantities of taconite mining byproducts can be used for construction aggregate purposes on an expanded basis.

The NRRI is conducting a comprehensive three-year (2006 - 2008) research and demonstration program designed to: 1) identify new and economically viable uses for Minnesota Iron Range taconite aggregate, i.e., Mesabi Hard Rock™, material in road construction, road repair, and other applications where crushed stone aggregate is needed; and 2) conduct demonstration projects inside and outside Minnesota, including several targeted Upper Midwest states. A cooperative and collaborative research approach is being taken that involves the staff and facilities of the University of Minnesota in Duluth and the Twin Cities; the Minnesota Department of Transportation (Mn/DOT); Minnesota state agencies and organizations; upper Midwest and Great Lakes state DOTs; the taconite industry; and other public and private sector transportation and aggregate industry professionals, organizations, and individuals.

The program has two major phases. Phase I is aimed at assessing resource potential and road construction market opportunities by compiling and generating historical and new technical information on taconite aggregate applications, its unique properties and benefits, different mix designs and their attributes (especially when blended with less durable materials), innovative products and technologies, and to build awareness and interest in the expanded use of taconite aggregate products at the regional and national scale. Material transportation logistics and costs, and market opportunities and approaches to demonstrate taconite aggregate's advantages, will also be assessed during this first phase. Phase II will expand on Phase I findings and use them as a guide for demonstrating the actual use of taconite aggregate products on a larger scale throughout Minnesota and the Midwest in a variety of potential construction applications.

Research activities conducted to date include: concept introduction; compilation of historical uses of taconite aggregate usage in Minnesota roads; communications and marketing efforts; geological correlation and identification of potential aggregate units at the taconite mines and related mineralogical work; aggregate testing of bulk samples collected from four units at two of the mines; mix design and testing; development and testing of taconite aggregate-based innovative concepts and products; field demonstrations; and addressing the economic and logistical challenges of long-distance aggregate transportation.

Acknowledgements

The following project participants are acknowledged for their significant contributions: geologist John J. Heine of the NRRI's Economic Geology Group; Richard Kiesel and Blair Benner of the NRRI's Coleraine Minerals Research Laboratory; the Minnesota Department of Transportation (Mn/DOT) Office of Materials; Professors Mihai Marasteanu and Lev Khazanovich of the University of Minnesota's Department of Civil Engineering and Pavement Research Institute; iron-formation geologist/mineralogical consultant Harlan (Pete) Niles (retired); taconite aggregate pavement consultant Duane Marvin Hill (retired); microwave technology consultants David M. Hopstock, Ph.D., and David Lindroth of David M. Hopstock and Associates, LLC; and transportation issues and logistics consultants Elwyn Tinklenberg, David Christianson, and staff of the Tinklenberg Group. The staffs of Mittal Steel USA – Minorca Mine (formerly Ispat-Inland Steel), United Taconite LLC (formerly Eveleth Taconite), USX Minntac, and Hibbing Taconite Company are also thanked for providing mining property access for conducting mapping and sampling, logging and sampling drill core, and reviewing drill core records.

PROJECT OVERVIEW

Introduction of Concept: Why Taconite Aggregate?

For over 100 years, iron ore has been mined from Minnesota's Mesabi Iron Range. Historically, the Mesabi Range has been the most significant iron mining district in the Lake Superior region (fig. 1) and United States. The high grade hematitic ores mined from the Mesabi Range during the first 50+ years of the 20th century were eventually replaced by the lower grade, but volumetrically extensive, magnetite-bearing taconite ores that are mined today.

"Taconite" is an economic term for iron-formation from which iron can be profitably extracted after fine-grinding, followed by magnetic separation and pelletizing (Morey, 1993). Presently, six taconite mines are operating in Minnesota (fig. 2). A seventh, Cliffs Erie (LTV), closed in 2001. About 100 million tons of taconite rock must be blasted and removed – every year – just to get at the taconite ore that is made into taconite pellets. To put this number in perspective, 100 million tons equals:

- >4 million truckloads
- ten thousand 100-car, at 100 tons per car, unit trains
- two thousand 1,000 ft. ore boats

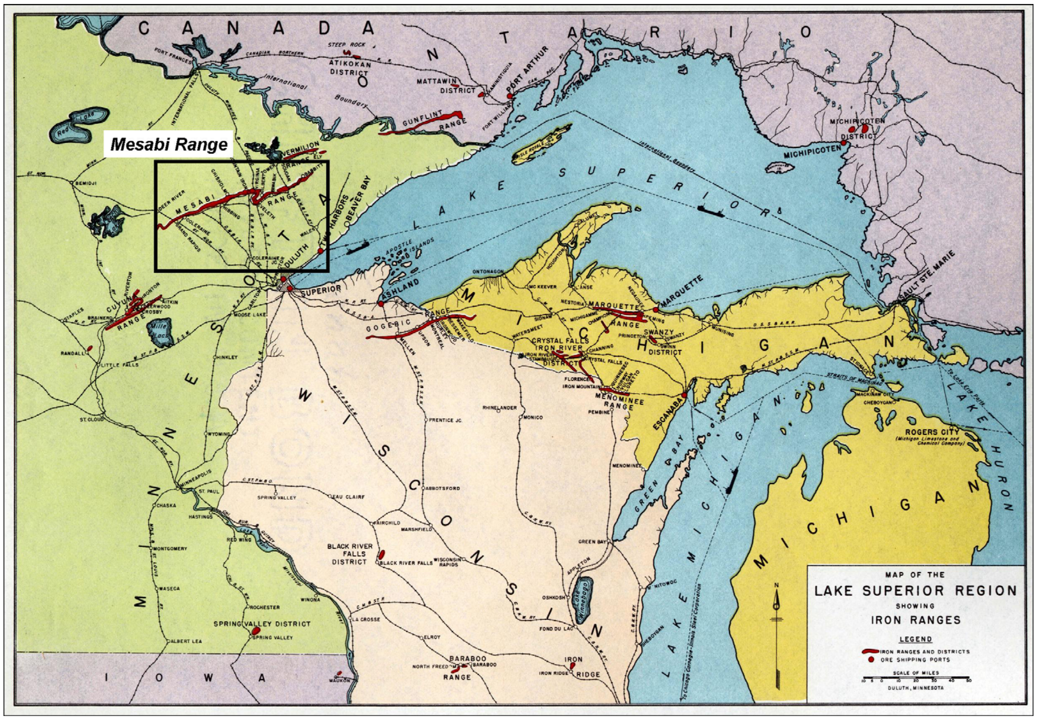

Figure 1. Mesabi Range (boxed area) relative to historic Lake Superior region iron ranges. Map source: Oliver Iron Mining Division, United States Steel Corporation (Goldich and Marsden, 1956).

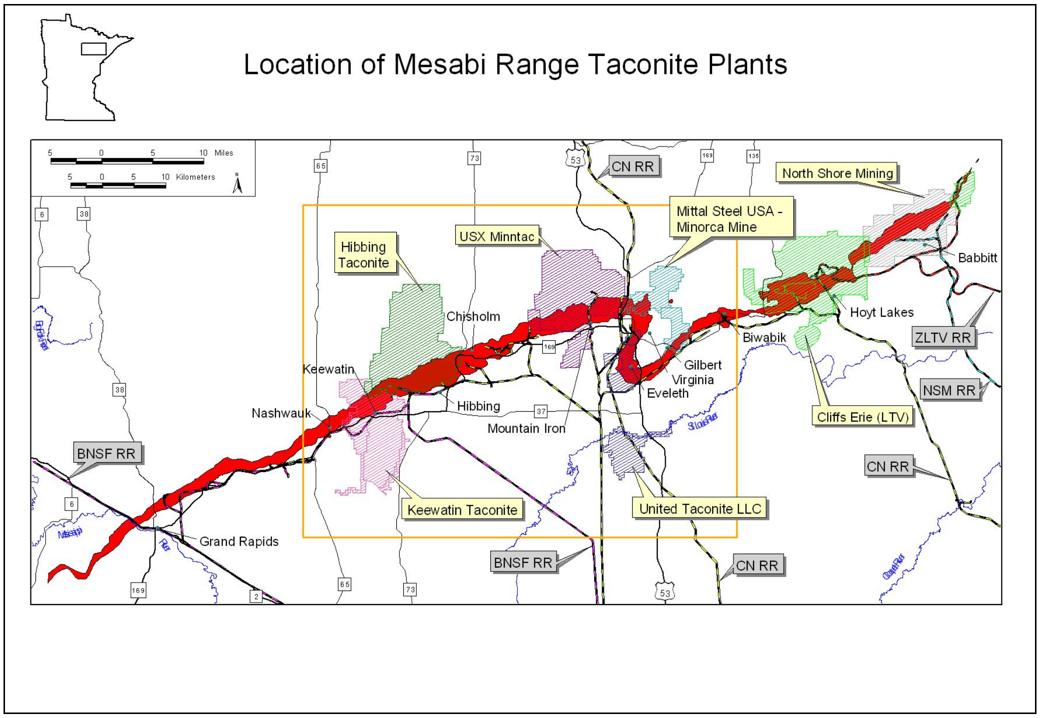

Figure 2. Location map of Minnesota Mesabi Range taconite mining operations. The light-colored box indicates focus area of NRRI's coarse tailings study (Zanko et al., 2003b).

Another 25+ million tons of coarse taconite tailings – the size equivalent of fine aggregate – are also generated annually. Because magnetite constitutes less than one-third of the weight of crude taconite ore, large amounts of tailings are generated during the taconite process.

Consequently, three major types of potential aggregate materials are represented by the combined 125+ million tons of taconite industry byproducts. They are:

- Fine Aggregate: 3/8 inch minus (coarse tailings and fine tailings)
- Construction/pavement aggregate: <2.5 inch (cobber rejects and ballast)
- Coarse products: >2.5 inch (shot rock; lean ore and "waste" units)

What makes this information about taconite materials significant? It means that Minnesota's taconite industry generates more mining and processing byproducts in a single year than what the entire state uses for aggregate in two. This is not to suggest all of the taconite materials are suitable or available for use; however, the potential is still enormous.

One year ago, Tepordei and Bolen (2006) made the following observation:

> "The total projected cumulative production of aggregates — crushed stone and construction sand and gravel — during the next 25 years is estimated to be 92 billion tons, slightly more than the total amount of aggregates mined between 1900 and 1999. These projections suggest that very large quantities of crushed stone and construction sand and gravel will be needed in the future **and will have to come, at least in part, from resources yet to be delineated**" (our emphasis).

Pressure on our country's high quality aggregate resource supply, as described by Tepordei and Bolen, has been growing for several years. Aggregate shortages have already occurred in many parts of the country, and have been predicted for the 7-county Metro Area of the Twin Cities in Minnesota (Southwick et al., 2000).

Since the year 2000, the Natural Resources Research Institute (NRRI), University of Minnesota Duluth, has been investigating how the tremendous quantities of taconite mining byproducts can be used for construction aggregate purposes on an expanded basis. With support from the U.S. Department of Commerce, Economic Development Administration (EDA), the University of Minnesota, and other state-based organizations and foundations, the NRRI is continuing this effort by leading a comprehensive three-year (2006 - 2008) research and demonstration program designed to: 1) identify new and economically viable uses for Minnesota's Mesabi Iron Range taconite aggregate, i.e., Mesabi Hard Rock™, material in road construction, road repair, and other applications where crushed stone aggregate is needed; and 2) conduct demonstration projects inside and outside Minnesota, including several targeted Upper Midwest States (Fosnacht et al., 2006, 2007). The remainder of this paper is dedicated to describing this ongoing program.

History of Taconite Byproduct Use as Aggregate Material

While laboratory testing and material characterization are important components of the taconite aggregate research program (as discussed later in more detail), the fact of the matter is taconite industry byproducts have been used in aggregate applications for years in miles of Minnesota roads. Coarse taconite tailings and crushed taconite rock (Mesabi Hard Rock™) have been staples of the road construction industry on Minnesota's Mesabi Iron Range for over four decades (Oreskovich and Patelke, 2006). Comparable to trap rock in quality, taconite aggregates have proven to be strong and durable when used as subgrade and base material and in bituminous pavements (fig. 3). The superior hardness and durability of these materials make them a viable candidate for exporting to the Twin Cities metro and out-state areas and to surrounding states as stand alone aggregate or for blending with local aggregates to produce more competent pavements.

Figure 3. Coarse taconite tailings used in U.S. Hwy 53 / 169 interchange project north of Virginia, MN, 2004-2005. Upper photo shows tailings used as base material for bridge abutment construction. Lower photo is viewing north of main intersection loop (Oreskovich and Patelke, 2006).
Photo used with permission: photographer David A Witt/Aero-Environmental Consulting
http://www.aero-environmental.com.

Unfortunately, the use of aggregate material from the Mesabi Range in not widely known outside of northeast Minnesota. Documenting how and where taconite byproducts have been used in Minnesota (fig. 4), along with assembling related test and longevity data, is near completion and will provide potential end users with a basis for considering these materials in combination with (or in place of) other aggregate sources. This information is being documented and assembled in GIS format. Supporting test data and relevant construction information are linked to the location records to provide a basis for state transportation departments around the country to evaluate taconite aggregate for their own construction needs. Included in the GIS product are the various available aggregate products, the applications they have been used for, the locations of use, and supporting documentation, such as Mn/DOT design plans, specifications, and test data. The purpose is to provide an accessible resource to engineers, designers, contractors, and others for determining the applicability of taconite aggregate products for their individual needs.

Nearly 100 individuals, including engineers, administrators, technicians and operators (current and retired) from state, county, and municipal governments and government agencies, engineering firms, construction companies, testing laboratories, consulting firms, taconite mining operations, and industry support groups are contributing to this compilation of the historical use of taconite byproducts as construction aggregates in the State of Minnesota.

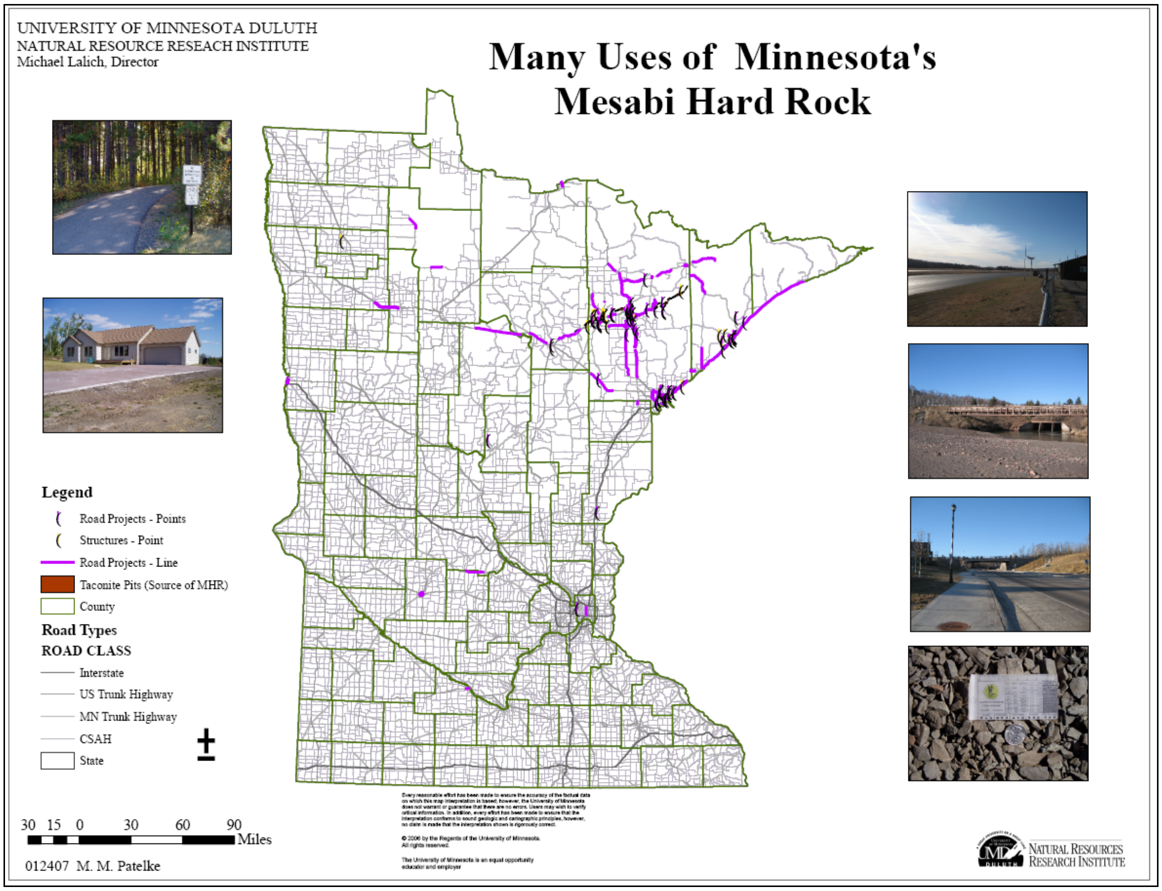

Figure 4. Uses of Mesabi Hard Rock™ in Minnesota.

Communicating and Marketing Taconite Aggregate

In order to position the potential taconite aggregate byproducts that can be used from the Mesabi Iron Range, a significant communications and marketing effort has been undertaken. This has entailed developing communication pieces that address: 1) issues associated with substituting taconite based products for local materials; 2) material handling and logistical challenges to overcome in bringing the materials to the desired locations; and 3) how to incorporate the approval of taconite material use in local jurisdictions. A variety of aggregate materials are used throughout the Midwestern region of the United States in highway construction, and taconite byproducts will have to compete with and/or augment these existing materials based on both their physical attributes and the net value they will bring to a road project.

A decision was made early in the research program to "brand" taconite aggregate as Mesabi Hard Rock™ to make it more recognizable to potential users. A comprehensive information package (brochure, and data and report CD), including a Mesabi Hard Rock™ logo, were assembled in time for distribution at the October 2006 American Association of State Highway and Transportation Officials (AASHTO) annual meeting and trade show in Portland, OR, and for ongoing project-related interactions (fig. 5, in which both sides of the fold-out brochure are shown).

Performance

The performance of MESABI HARD ROCK™ taconite mining aggregate is second to none. It is an extremely dense material that is less susceptible to breaking down under heavy loads, thereby extending the life of paved roadways. It is specifically engineered through a controlled crushing process, resulting in superior angularity and better asphalt adhesion. As a byproduct of taconite processing, MESABI HARD ROCK™ contains less sand, which means better, more consistent overall aggregate quality.

The racing industry, for example, is extremely enthusiastic about the use of this product. MESABI HARD ROCK™ taconite aggregate has been used on the Brainerd International Raceway, to rave reviews. Racecar driver Ed Shaughnessy says, "The track is absolutely awesome! It's smooth because of the high density of the taconite tailings in the asphalt. The higher the density, the better my tire performance."

A recent study of I-90 pavement failure in South Dakota suggests improving pavement performance by finding a new source of aggregate. Another recent study of a common aggregate problem notes that, "More and more states have taken to ordering their aggregate supplies from out-of-state or even foreign sources, so finding a reliable…source has been, at best, unpredictable."

A reliable, abundant source is available and ready — right here in Minnesota!

"The use of taconite mining aggregate offers important environmental advantages: it's a pre-existing byproduct that requires very little additional processing, it reduces the need for new aggregate extraction sites, and it aids in the clean-up of existing mining operation. It's a win for everybody — especially the environment."

Don Fosnacht, Center Director
Natural Resources Research Institute
University of Minnesota Duluth

Safety

MESABI HARD ROCK's™ high friction factor means superior skid resistance. Because of its hardness, it retains its abrasive quality, resulting in improved traction and reduced surface polishing. The consistent quality of the material ensures it easily meets all requirements for highway construction. Everyday drivers can appreciate the same pavement qualities that racecar drivers demand - a hard aggregate-paved surface with great traction.

Extensive testing at the Natural Resources Research Institute in Duluth, Minn has proven the superior strength and durability of taconite mining aggregate. When combined with advanced asphalt binders, it can help reduce the hazards of rutting and other pavement failures.

The aggregate is non-porous and absorbs less moisture than other paving materials, making it better able to withstand the effects of freeze/thaw cycles. Fewer cracks, potholes and other damage to the pavement result in safer driving for everyone on the road.

Environment

The future of aggregate supplies is in recycled or waste materials.

Current federal highway funding, under the Transportation Equity Act for the 21st Century, will increase demand for aggregate by approximately 156 percent. Most of this demand will be for "clean" or "washed" products.

MESABI HARD ROCK™ is a clean, recycled product - a byproduct generated in the processing of taconite. Large amounts of taconite mining aggregate – enough to supply our transportation needs for decades – are readily available in Northern Minnesota.

Development of new sites requires compliance with environmental and zoning restrictions and regulations, particularly in urban areas. Public perception of aggregate production facilities is also a factor. No one wants a new mine opened in his or her neighborhood.

Utilizing this high-performing extant byproduct would eliminate permitting, opening or expanding mining sites and would require very little additional material processing.

"Recently we paved the access road to the Lake County Fairgrounds with 100 percent taconite tailing bituminous mix. I've been with Lake County for 20 years and I expect the taconite tailing mix will last at least that long."

Alan Goodman,
Lake County Highway Engineer

Mesabi HARD ROCK™

The geological formation of the Mesabi Iron Range

JAMES L. OBERSTAR

COMMITTEE ON TRANSPORTATION AND INFRASTRUCTURE

Congress of the United States
House of Representatives
Washington, DC 20515–2308

July 11, 2006

Dear Partner in Transportation:

Two of the more vexing issues in highway construction are pavement durability and the diminishing reserves of aggregate: each is vital to the future of our surface transportation program.

Fortunately, there is a readily available material that can resolve both issues: taconite tailings. Billions of tons of this material are stored in accessible stockpiles on Minnesota's Mesabi Iron Range in my congressional district. Tailings are generated in the process of extracting iron units from taconite, an iron bearing ore which is harder than granite.

Taconite aggregate is a tough material which maintains its abrasion and traction quality. Tested for several years in "real-world" highway segments, this engineered product, with high angularity and low fines, outperforms standard aggregate, resisting even the freeze/thaw cycle along the North Shore of Lake Superior.

Best of all, taconite aggregate is available in stockpiles in several mines along the Mesabi Range, where it can be excavated without the permitting process required for development of new aggregate sites.

Attached is important information on this product, to which I invite your careful consideration. Taconite aggregate will enhance the performance of our highways, extend their life cycle and reduce construction impacts on our environment, and assure a long-term supply of durable, cost-effective material that is also environmentally friendly. With your help, we can put taconite aggregate to the beneficial service of the entire surface transportation program.

With best wishes.

Sincerely,

Jim Oberstar
James L. Oberstar, M.C.

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U.S. Department of Commerce Economic Development Administration
University of Minnesota Duluth Natural Resources Research Institute
Iron Range Resources
Minnesota Technology
Minnesota Power
The Blandin Foundation

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The University of Minnesota is an equal opportunity educator and employer.

Coarse aggregate of the highest durability and strength.

Long-lasting and consistent aggregate providing superior traction and abrasion on paved surfaces.

A recycled taconite byproduct available in large, readily available quantities.

Mesabi HARD ROCK™
High performance taconite aggregate

WHAT IS MESABI HARD ROCK™?

MESABI HARD ROCK™ is a high-quality, coarse mining aggregate that is the byproduct of taconite, an enriched iron ore substance. An extremely durable and high-performing aggregate, MESABI HARD ROCK™ is easy on the environment because large quantities are available without creating or expanding gravel sites. The MESABI HARD ROCK™ project, conducted at the University of Minnesota Duluth Natural Resources Research Institute, is focused on demonstrating the characteristics of taconite ore tailings, crushed rock, and associated mine out-turns as aggregate for use as fill, roadbeds, surfacings and construction projects. Over 100 million tons of MESABI HARD ROCK™ are produced per year (and volumes are growing) with an existing inventory readily available at five taconite mine sites on the western Mesabi Iron Range in northern Minnesota.

TRANSPORTATION MODES

While trucking may be used near the mines in northern Minnesota and Wisconsin to distribute MESABI HARD ROCK™, other markets will need alternative transportation. Fortunately, well over a century of iron ore and taconite transport has developed a major freight infrastructure. Long haul rail connections are available year-round to move the aggregate in volume from the mining sites, south through Wisconsin to Chicago and beyond, to and through Minneapolis and St. Paul, then south and west to Iowa and the Plains states, and directly to and through the Dakotas. Transloading at the Twin Ports of Duluth and Superior allows very large bulk movements of material via the Great Lakes marine carriers to port cities to the south and east into those markets adjacent to Lakes Michigan and Erie, in particular. Intermodal options are also being studied, including roadrailer-type equipment and containerization for specialty uses such as high-friction surfaces, bridge decks and patching materials.

TRANSPORTATION ECONOMICS

The demonstrated economics of a variety of high-volume and competitive cost transportation models are being explored, such as:

- Unit and shuttle trains
- Rapid discharge cars and high-volume terminal facilities
- Purpose-built shipper-leased or owned equipment
- Joint use facilities
- Partnered transloading sites

Lakes shipping and other volume rates will depend on identifying very high volume, long-term movements, while rail, truck, intermodal and terminal costs will hinge on operating plans that can deliver high equipment and facility utilization. The MESABI HARD ROCK™ project works actively with existing markets as well as future markets facing material shortages. Logistics analysis of possible backhauls, such as ethanol plant feedstocks, biowaste fuels and urban area garbage transport and disposal will be included in the studies, and siting of aggregate preparation plants (screening, washing and mixing) will enter into the business viability evaluations.

Figure 5. Mesabi Hard Rock™ brochure – Side 1 (top) and Side 2 (bottom).

Geology of Minnesota Taconite

The long-term prospects for taconite byproducts being a major source of construction aggregate will depend on material consistency. Therefore, the research program will also focus on materials that provide the best potential for long-term product uniformity. Just as geology and mineralogy control ore quality at the mines, these factors will also control byproduct quality and uniformity - within and between mines – and dictate how much of those 125+ million tons have true aggregate potential.

NRRI and mine geologists are working with Mn/DOT geologists and engineers to define the geological and mineralogical criteria needed to best assess, sample, and characterize byproducts derived from the iron-formation for aggregate use. Site visits, field mapping, core and sample examination, microscopy, and X-ray diffractometry will all be used to accomplish this task.

General geology

NOTE: The following geological overview references NRRI geologist Mark Severson's contributions to a previous investigation of Minnesota's oxidized taconite resources (Zanko et al., 2003a), and is offered as a primer on the geology of Minnesota's Mesabi Iron Range.

The iron ores of the Mesabi Range (fig. 6) of northeastern Minnesota are associated with the Biwabik Iron Formation, which is one of three formations that comprise the Paleoproterozoic (2,500-1,600 Ma) Animikie Group. They are described as follows:

- At the base of the Animikie Group is the Pokegama Quartzite, which consists of a clastic sequence of quartz arenite and interbedded argillaceous rock;
- Overlying these clastic rocks are the iron-rich sedimentary rocks of the Biwabik Iron Formation (BIF). NOTE: The term "iron-formation," refers to bedded, layered, or laminated sedimentary rock that contains 15 percent or more iron. The BIF was derived from a mixture of chemical, volcanic, and epiclastic sources (Morey and Southwick, 1993), coupled with localized biogenic activity;
- Third, and at the top of the Animikie Group, is the Virginia Formation, which is comprised of a thick sequence of interbedded shale and graywacke.

Each of these stratigraphic units was deposited more or less continuously in sedimentary environments that ranged from shallow water sediments of the Pokegama Quartzite to deep water sediments of the Virginia Formation. Age dates for rocks beneath the Animikie Group (Beck, 1988; Hemming et al., 1990), and from an ash layer within the time-synchronous Gunflint Iron Formation in Canada (Fralick and Kissin, 1998), suggest that deposition of the Animikie Group began sometime between 2,125 and 1,930 million years ago, and continued beyond 1,878 million years ago.

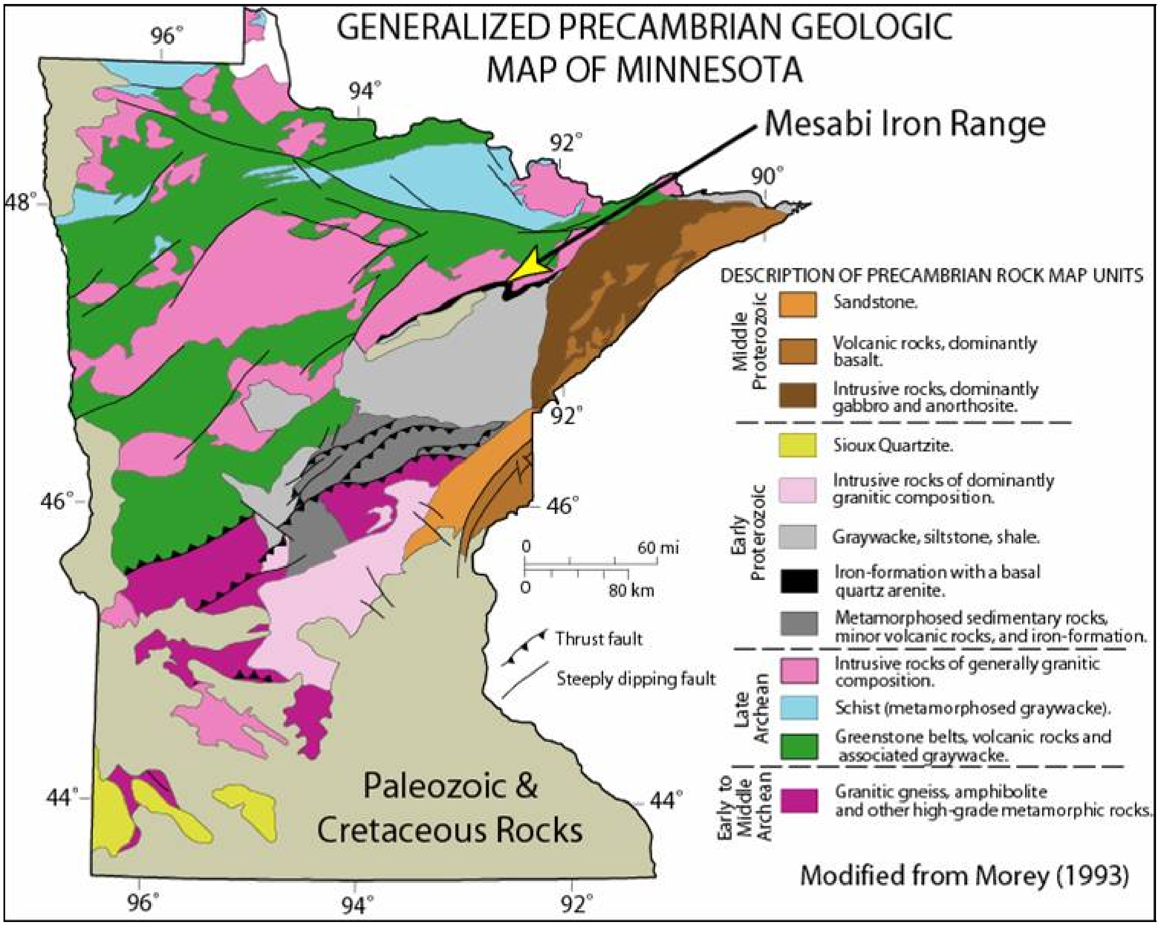

Figure 6. Geologic map of Minnesota; modified from Morey (1993).

Stratigraphy of the Biwabik Iron Formation

The Biwabik Iron Formation (BIF) has typically been subdivided into four members that include (from bottom to top): Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty (fig. 7). The cherty iron formation members are generally thick-bedded and contain rounded grains (0.5-2.0 mm) of chert that are referred to as granules. These “cherty” members typically contain higher percentages of iron oxides (magnetite, hematite, and/or goethite). In contrast, the “slaty” members are thin bedded (0.5-3.0 mm thick beds) and very fine-grained. They are composed mostly of iron silicates and iron carbonates (Fe-silicates and Fe-carbonates, respectively). Both cherty and slaty iron-formation types are interlayered at all scales. However, one rock type often predominates in each of the four lithostratigraphic members, and are so-named due to this dominance, i.e., thick-bedded cherty iron-formation is dominant in the Lower Cherty member, whereas thin-bedded iron-formation is dominant in the Lower Slaty member. The “cherty” and “slaty” members are envisioned to have been deposited on a continental shelf in “shallower” and “deeper” water, respectively (Ojakangas, 1983). Overall, the change from cherty to slaty members is indicative of two cycles of progressive deposition in shallow water to deeper water that form an earlier cycle of Lower Cherty (shallower) to Lower Slaty (deeper) followed by a later cycle of Upper Cherty (shallower) to Upper Slaty (deeper).

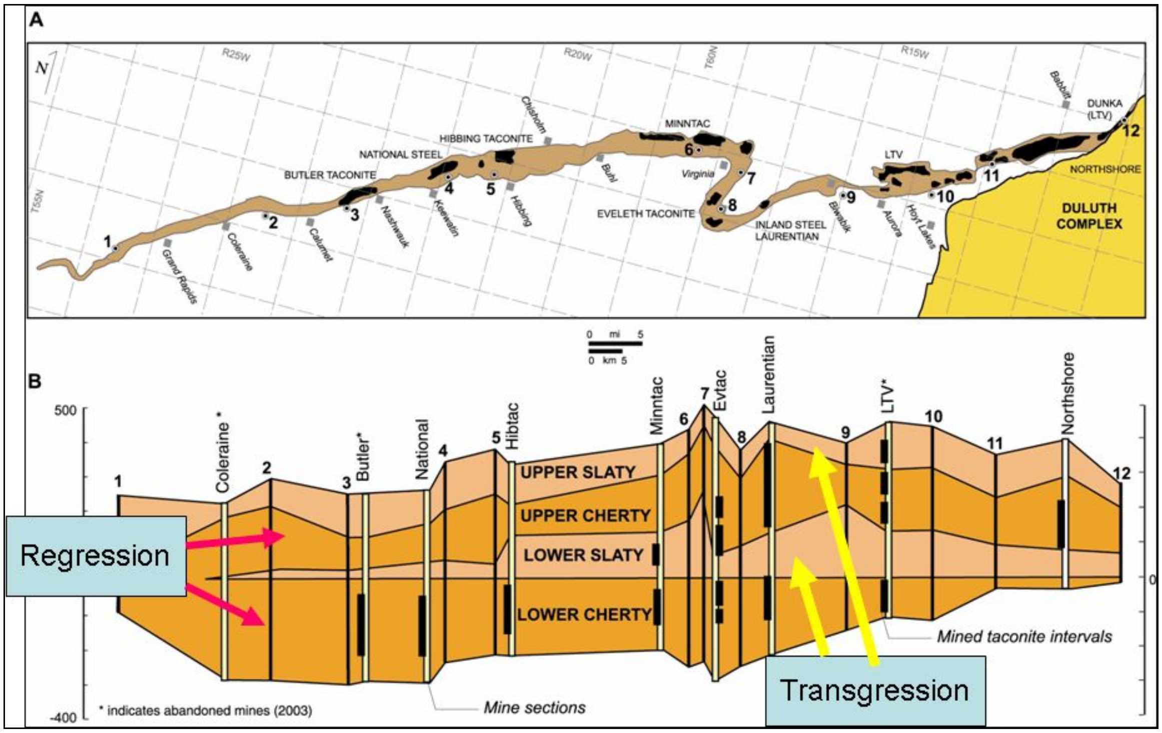

Figure 7. Generalized stratigraphy of Biwabik Iron Formation, modified from Djerlev (Graber et al., 1993).

This four-fold stratigraphy within the BIF has long been recognized as the fundamental basis for mining activity at each of the currently operating (and inactive) taconite mines/mining areas along the length of the Mesabi Range. Over the years, however, each of the mining companies has developed their own set of criteria (frequently grade-driven) for further subdividing the BIF and naming individual submembers according to their individual experiences and needs. Consequently, the ability to correlate submembers from one mine to the next based on mining company records alone has been complicated by these differing nomenclatures.

Implications for aggregate potential

In response, geologist Mark Severson is leading NRRI's efforts to develop a "unified" stratigraphic nomenclature for the BIF by correlating information available at each of the individual mine sites along the entire Mesabi Range. This work, still in progress, is being accomplished though a systematic review of company records, re-logging of available drill core, and in-pit mapping. This revised (and draft) view of the BIF is illustrated in Figure 8 (Severson, 2006), in which the stratigraphic units are referenced against ("hung" on) the base of the Intermediate Slate, i.e., base of the Lower Slaty. Most of the correlations are based on sedimentological textures that are described for the various "cherty" and "slaty" iron-formation types.

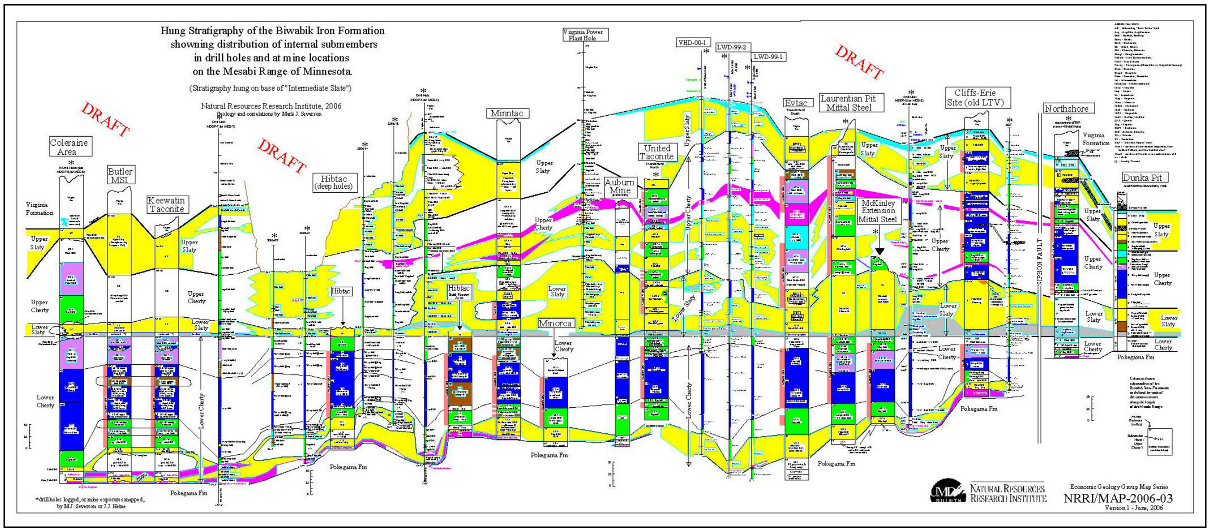

Figure 8. Hung stratigraphy of the Biwabik Iron Formation: draft version (Severson, 2006).

Importantly, these geological correlations are also being used for refining and identifying potential aggregate horizons within the BIF for sampling (fig. 9), and are critical to defining potential aggregate horizons that are considered to be waste rocks by the taconite mining companies on the Mesabi Range. To improve our understanding of this aggregate potential, over 75 drill holes have been logged to determine the stratigraphy of the Biwabik Iron Formation at Mittal Steel USA (proposed McKinley Extension pit), United Taconite LLC, Minntac (United States Steel Corp.), and Hibbing Taconite Company. Thus far, preliminary geologic correlations indicate that the most voluminous amount of potential aggregate material is present at the proposed McKinley Extension (fig. 10). At this locale, material in drill core that is very similar to "Mesabi Select" (a potential aggregate horizon previously identified at United Taconite) is present as channels throughout the Lower Slaty (fig. 11), as well as in the underlying Lower Cherty. However, testing of this material is still needed to determine its actual aggregate potential. Similar "Mesabi Select" material at Minntac has been defined in one drill hole thus far. Drill holes preserved at Minntac have been identified and inventoried for defining potential aggregate horizons, and will be logged in the near future.

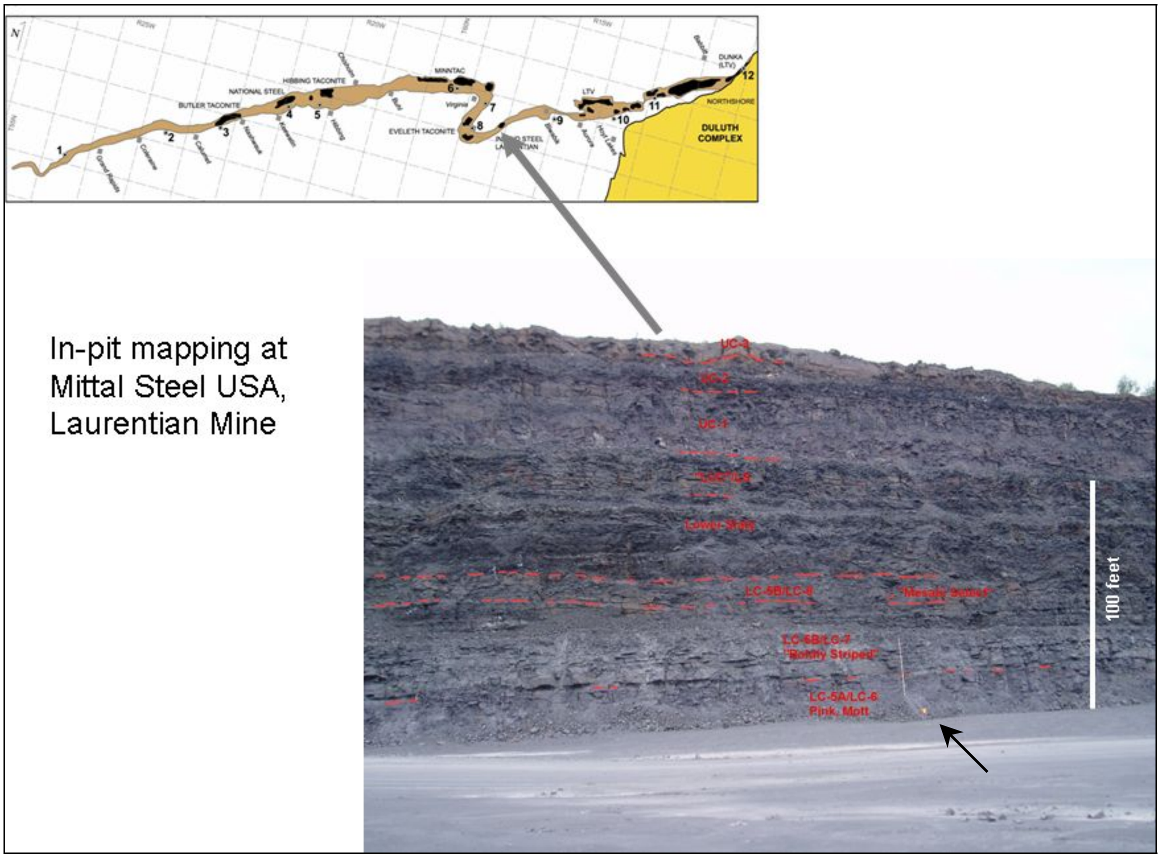

Figure 9. In-pit mapping at Mittal Steel USA Laurentian Mine showing mine face and stratigraphic units (note arrow pointing to geologist; scale bar equals 100 feet).

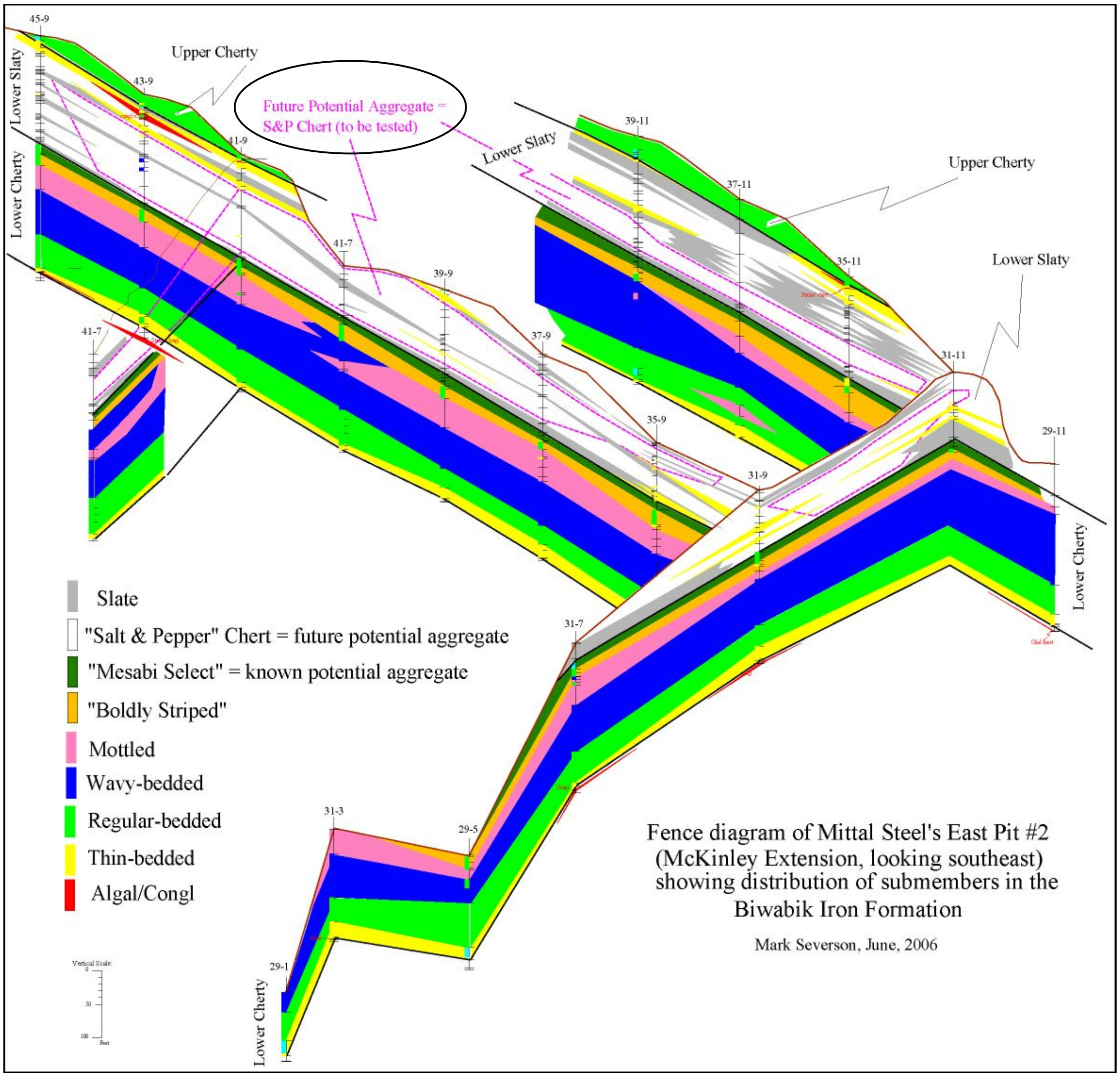

Figure 10. Fence diagram showing potential aggregate interval within Biwabik Iron Formation.

Figure 11. Drill core example of potential aggregate horizon between arrows. The interval represents channel deposition within the Lower Slaty submember of the Biwabik Iron Formation.

Sample Acquisition and Preparation

Fundamental to the research program is the availability of byproduct samples for testing and covering all research and demonstration project contingencies. Based on the geological work described previously, four bulk samples representing four different potential aggregate horizons, each weighing 1,500 to 1,750 pounds, were collected from blasted "waste" rock muckpiles at Mittal Steel USA and United Taconite (fig. 12). The four samples were:

- LC-5A: Lower Cherty, Submember 5: Mittal Steel USA, Laurentian Mine
- LS-2: Lower Slaty, Submember 2: Mittal Steel USA, Laurentian Mine
- LUC: Lower Upper Cherty: United Taconite LLC, Thunderbird Mine
- LC-8: Lower Cherty, Submember 8 ("Mesabi Select"): United Taconite LLC, Thunderbird Mine

The muckpile samples had a top size of 6 inches, and were crushed and screened by NRRI's Coleraine Minerals Research Laboratory (CMRL) to the following specifications for aggregate testing by the Minnesota Department of Transportation (Mn/DOT): 325 pounds each of 3/4 inch to 1/2 inch, 1/2 inch to 3/8 inch, and 3/8 inch to #4; along with 2 pounds of #4 to #8, 4 pounds of #8 to #16, 4 pounds of #16 to #30, 4 pounds of #30 to #50, and 3 pounds of #50 to #100.

Additional sample preparation (crushing and screening) has been performed on other taconite byproduct materials ranging in size from coarse taconite tailings (equivalent to fine aggregate, i.e., -3/8 inch) to ballast sized (-3 inch / +1.5 inch) taconite aggregate. Several tons of the latter were crushed to spec and are being tested by the University of Minnesota's Department of Civil Engineering in both asphalt concrete and portland cement concrete (PCC) applications.

Figure 12. Sampling of post-blast taconite muckpile.

Aggregate Testing

Aggregate testing is being conducted – in conjunction with the Minnesota Department of Transportation's (Mn/DOT) Office of Materials and the University of Minnesota's Department of Civil Engineering – to characterize the taconite mining byproducts. Side-by-side comparisons to traditional aggregates and blends that use both will give potential end-users important technical and performance information.

Mn/DOT physical testing

The four bulk samples have been undergoing aggregate testing by Mn/DOT's Office of Materials in Maplewood, MN, and physical testing has been completed. In summary, the tests showed the taconite rock to generally meet or exceed the durability criteria set for Class A rock (table 1). For example, Los Angeles Rattler (LAR) values for typical Class A rock types, i.e., granite, quartzite, basalt, averages about 20%, while magnesium sulfate loss averages about 2%. For carbonate aggregates, the average LAR is about 30%, and the magnesium sulfate loss average is about 10%. For aggregates in general, the specs can vary upward depending on the use of the material: for LAR from 35% to 40%, and for magnesium sulfate from 14% to 23% (Beaudry, T., Mn/DOT, pers. comm., 2006). In comparison, LAR for the four taconite samples ranged from 14% to 17%, and magnesium sulfate soundness ranged from 0% to 4%.

A study conducted by Wu et al. (1998) concluded that magnesium sulfate tests (along with Micro-Deval) provided the best correlations with field performance of asphalt concrete. The study showed that losses of less than 18% for both tests appeared to separate the good and fair performers from the poor performers. Coarse taconite tailings samples from NRRI's 2003 coarse taconite tailings study (Zanko et al., 2003b) were well below the 18% mark for both tests. Individual magnesium sulfate soundness test values ranged from 2.8% to 12.1%, while Micro-Deval values ranged from 8.4% to 15.8%.

Table 1. Mn/DOT taconite aggregate testing summary.

Mn/DOT testing summary	Average Specific Gravity	Average Absorption	Oven dry unit volume lbs/cu.ft.	Los Angeles Rattler	Mag. Sulfate Soundness	Average Flat and Elongation
100-05, LC-5	3.304	0.54%	107.7	14%	0%	1.00
102-05, LS-2	2.868	1.80%	92.0	17%	4%	2.15
111-05, LC-8	3.089	1.23%	100.1	17%	2%	6.00
114-05, LUC	3.117	1.07%	101.9	16%	2%	1.55
Granite	2.634	0.74%	95.4	20%	0%	0.00

Mn/DOT ASR testing

Mn/DOT has also been testing potential alkali-silica reactivity (ASR) in concrete by performing concrete prism tests (ASTM C 1293); these tests will continue for 2 years. Results after 182 days showed three of the four samples performing acceptably, while one sample (LC-5) showed unacceptably excessive expansion. These test results will aid in identifying which taconite aggregates can be used in portland cement concrete pavement applications, and which might be limited to bituminous asphalt-based pavements. Mn/DOT is also performing 14-day Rapid

Mortar Bar (ASR) testing (ASTM C 1260) as a supplement to the longer-term ASTM C 1293 test.

University of Minnesota mix design work and testing

Mix design work will largely be dictated by specific demonstration projects and products that are considered. A key part of this research will be to develop and test mix designs that: 1) use taconite aggregate exclusively; and 2) combine taconite aggregate with aggregate from other rock sources. The latter work will be important for assessing how pavement performance and durability might be improved in markets where the local aggregate quality is marginal, giving potential end-users useful technical and performance information. This will be very important in demonstrating the potential use of the materials to other parts of the region such as Iowa, Illinois, Wisconsin, Michigan, and Indiana.

The NRRI is working closely with Department of Civil Engineering faculty/researchers at the University of Minnesota's Pavement Research Institute specializing in asphalt and concrete mix design; with Mn/DOT District 1 engineers (current and retired) who have experience with using taconite byproducts in mix designs and in highway construction projects in northeastern Minnesota; and with Mn/DOT's Office of Materials. In addition, cooperative research on mix design is being pursued with the departments of transportation from other states to develop specifications for using and blending taconite materials with their local aggregate (to add a more durable non-polishing component, for example).

Our partners at the University of Minnesota's Department of Civil Engineering, Professors Mihai Marasteanu and Lev Khazanovich, will investigate and determine if the use of taconite aggregates is beneficial for bituminous asphalt mixtures and Portland cement concrete. This research will focus on performing standard and non-standard tests on laboratory prepared mixtures following a rigorous statistical design to determine significant improvements in mechanical properties compared to the control specimens. In addition, field cores extracted from pavements already constructed with taconite aggregates will be tested using the same protocols as the laboratory-prepared specimens.

In evaluating the properties of composite materials prepared with various percentages of taconite aggregates, particular attention will be given to evaluating the bonding properties between asphalt binder and portland cement paste, respectively, to the taconite aggregates. This investigation will be performed through moisture sensitivity tests for asphalt mixtures and freeze/thaw cycles for portland cement concrete, as well as through acoustic emission investigations for tests performed on asphalt mixtures at low temperatures.

Dynamic complex modulus (E*) tests, as well as low temperature cracking tests such as Indirect Tension (IDT) and Semicircular Bend (SCB) tests, will also be performed. This work will provide a direct comparison of the performance of taconite-based mix designs to previously tested limestone- and granite-based mix designs.

Innovative Concepts/Uses

Pothole patching compounds

Research by NRRI scientists shows that certain taconite byproduct materials can be used in non-asphalt-based cold-mix pothole-patching compounds. Potholes are a nationwide problem, especially in northern climates. The most common petroleum-based “throw-and-go” formulations are marginally effective and often perform poorly. NRRI believes its formulation may be a superior product. Limited field-testing of the patching product shows it to have excellent potential.

The research program is focusing on development of optimal mix formulations, expanded testing (laboratory and field demonstrations), and performance monitoring. Test patches installed in deteriorated concrete at the Federal Building in Duluth, MN, and subsequently top coated with a resin product that also used the taconite materials as an aggregate surface (fig. 13), show good wear and sustenance characteristics to date. Work in 2007 will investigate binders, binder mechanisms, aggregate material, installation/material handling, and physical quality characterization of the patch materials. Testing of these compounds will be conducted by the U of M’s Department of Civil Engineering, and at Mn/DOT’s MnROAD facility northwest of Minneapolis.

Figure 13. Top-coating of non-asphalt taconite-based patching compound at the Federal Building in Duluth, MN.

Microwave absorbing properties of taconite for pavement applications

Joint research conducted by Dr. David Hopstock and NRRI has shown that taconite is an excellent microwave absorber, which suggests that microwave technology could be used in pavement applications such as pothole patching and roadway deicing (Hopstock and Zanko, 2004). As described by Davis (1964), taconite is a hard, dense rock composed largely of an intimate mixture of quartz and magnetite (Fe_3O_4), plus varying amounts of iron oxides, carbonates, and silicates. Taconite's microwave absorbing properties are related to its mineralogy, specifically its magnetite content. The following chart (fig. 14) is based on the microwave heating of natural minerals performed by McGill and Walkiewicz (1987), and helps illustrate the concept of using magnetite-bearing aggregate. Note the arrows; they show the types of minerals commonly found in granitic aggregates, i.e., quartz, and feldspar (albite and orthoclase); and the analogue of limestone and/or dolomite, i.e., marble. All have poor microwave absorbing characteristics, which confirms that for the microwave deicing technology to be effective, typical pavement mixes need to be supplemented with aggregates that contain good microwave absorbing minerals. This characteristic means that pavements or paving products that contain taconite aggregate have the potential to be heated by a mobile microwave unit.

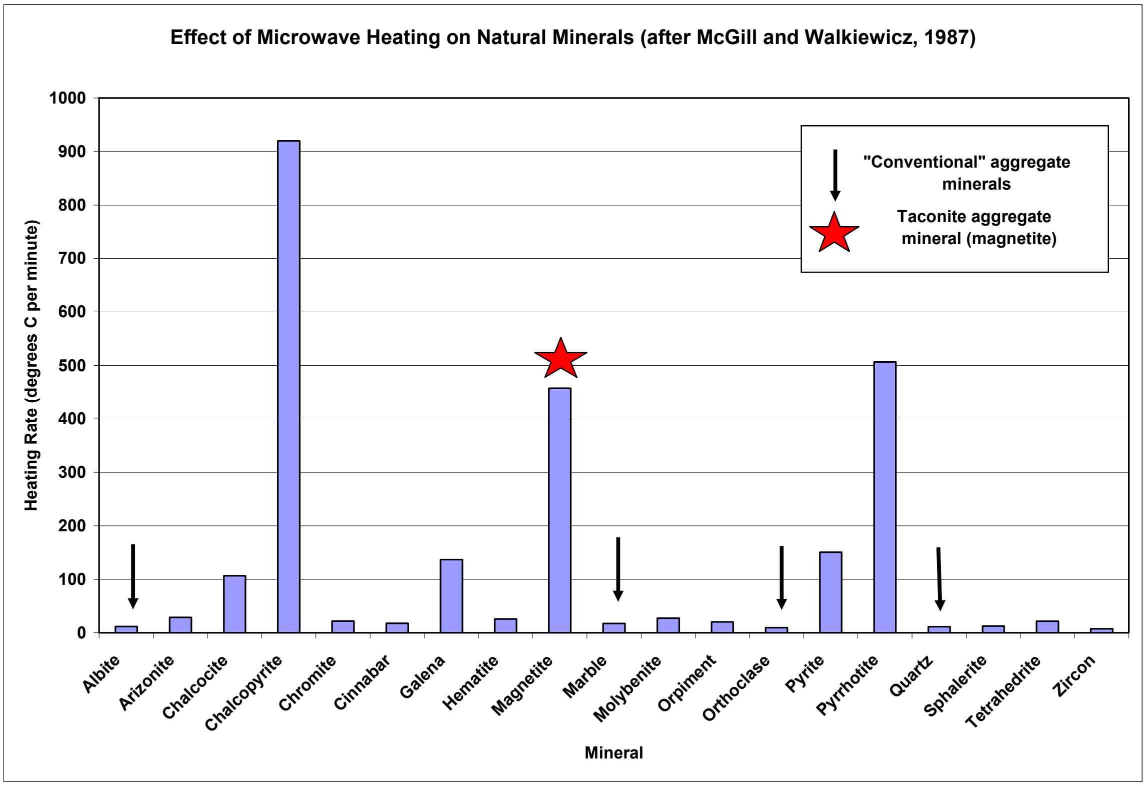

Figure 14. Microwave heating rates of minerals (after McGill and Walkiewicz, 1987).

Comprehensive bench and lab-scale testing is underway to better define optimal microwave and material parameters for various paving applications. Figure 15 illustrates the heating rates of the four taconite samples (LS-2, LUC, LC-8, and LC-5) discussed previously, a blank (plaster of paris), and conventional aggregates (quartzite, granite, limestone, and trap rock/basalt). Note that the taconite samples had the highest heating rates, while quartzite and granite had the lowest. Interestingly, the limestone sample exhibited moderate heating, perhaps due to the presence of iron-carbonate minerals. The trap rock/basalt sample exhibited the highest heating rate of the four conventional aggregates tested, due most likely to the presence of iron-oxide minerals. If one assumes an aggregate's microwave heating rate is proportional to its microwave-absorbing mineral concentration, aggregate made from typical crude taconite ore or processing byproducts would be easily superior to any of the other aggregates.

NRRI's Coleraine Minerals Research Laboratory (CMRL) performed Satamagan iron analyses on the -3/8 inch fraction of the four collected taconite samples. Values ranged from 2.56% (LS-2) to 23.61% Mg Fe (LC-5). This range of values has implications for microwave-enhanced pothole patching, de-bonding ice from pavements or airport runways, and re-heating and re-compacting portions of asphalt pavements that may otherwise suffer differential compaction and rutting. Presently, the ability to efficiently re-heat asphalt pavement for re-compaction and/or annealing is not readily available.

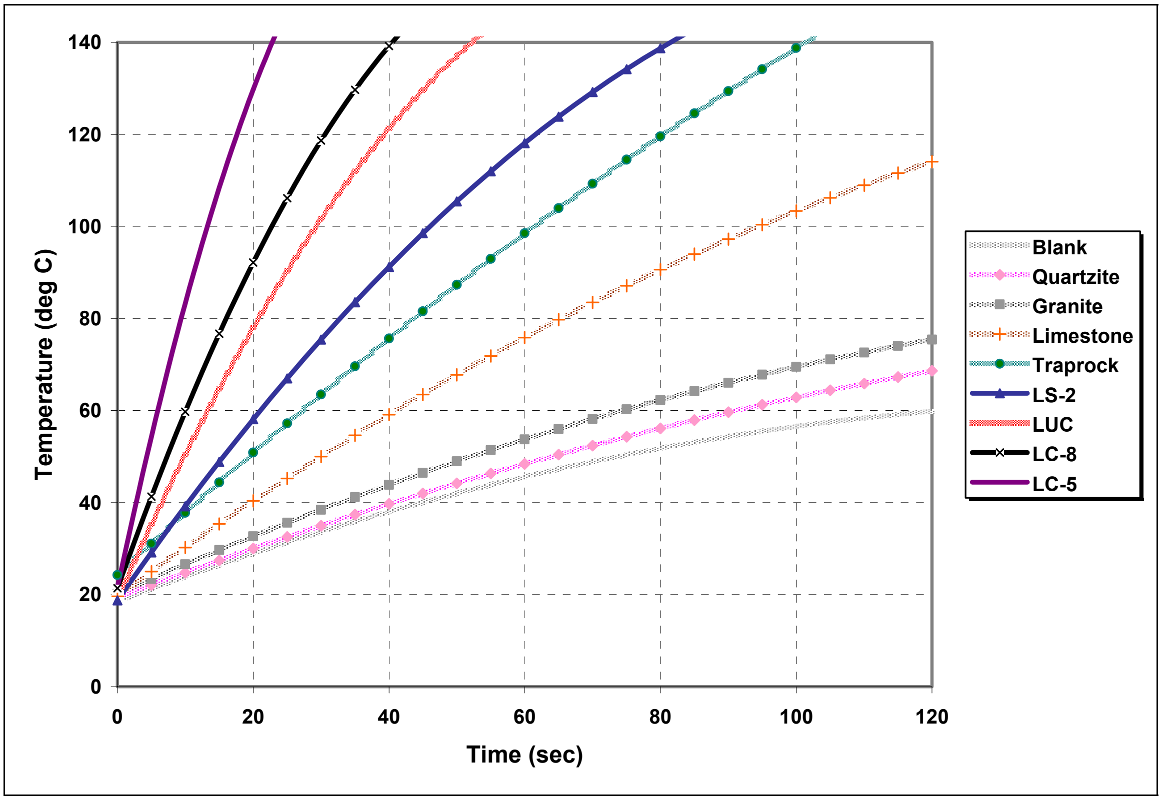

Figure 15. Heating rates of taconite and conventional aggregate.

Following laboratory work, the next step is to conduct scaled-up pavement testing and safety checking using a larger microwave unit. The ultimate goal will be to vehicle-mount a larger unit for use in actual mobile field tests. These tests could take place at NRRI, on a Duluth city street or parking lot, or at Mn/DOT's MnROAD test facility (see following discussion).

Demonstration Projects

In-state and out-of-state field demonstration projects are a key component of the overall taconite aggregate research program. The use of the material in actual operating applications is the best method of demonstrating its potential as a long lasting durable roadway material. Demonstration projects are intended to reflect a variety of surface applications, climatic conditions and traffic volumes and will generate practical data in real life settings.

MnROAD field demonstrations

Mn/DOT's MnROAD facility in Albertville, MN (40 miles northwest of the Twin Cities), is a cold-region testing laboratory that is unique to the world (fig. 16). The facility is an excellent pilot- to full-scale field research platform for testing and monitoring a variety of construction aggregate applications, including those that use taconite aggregate. As such, MnROAD will play a prominent role in the field-testing component of the taconite aggregate research program in the following areas:

- MnROAD performance monitoring for existing taconite test cells. In 2004, an asphalt test cell (Cell 31) and a portland cement concrete test cell (Cell 54) were constructed at MnROAD's Low Volume Test Road (fig. 17) in 2004 using "Mesabi Select" taconite aggregate
- MnROAD future test cell construction support
- Taconite use in maintenance treatments
- Mn/DOT taconite demonstration projects
- Pothole taconite patch material study
- Laboratory testing of taconite materials

Figure 16. Mn/DOT's MnROAD test facility in Albertville, MN, showing low-volume test road in foreground (loop) and I-94 to the right (photo source: Mn/DOT).

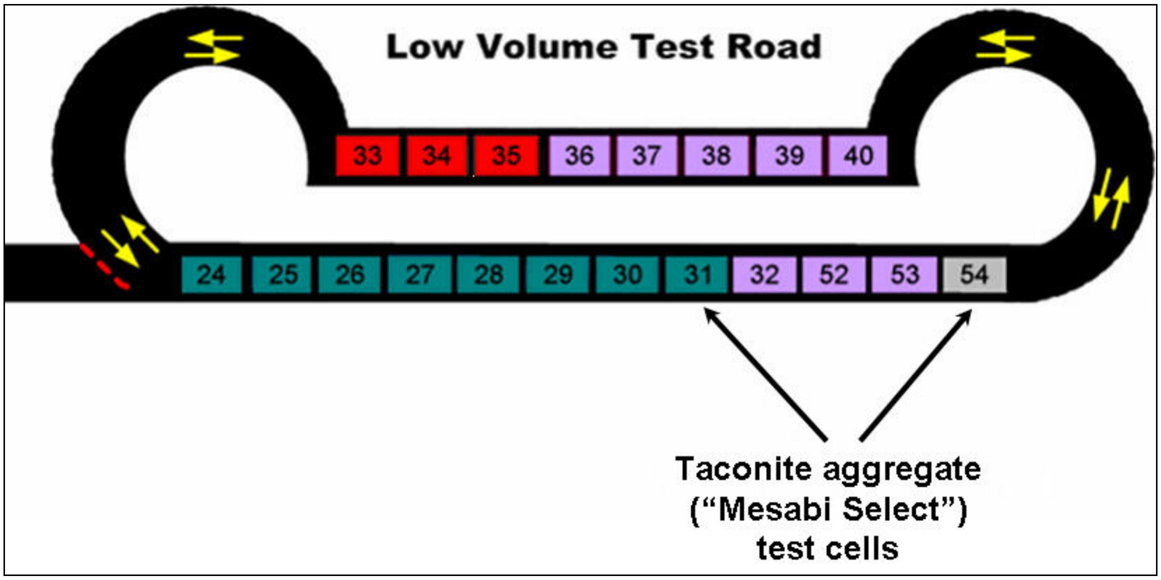

Figure 17. Schematic of MnROAD Low Volume Test Road (source: Mn/DOT).

Large-scale field demonstrations

A vitally importantly part of the project includes practical real life demonstration of the use of taconite materials in partnership with targeted state Departments of Transportation (DOTs), aggregate producers, and pavement contractors. Such field demonstrations will help advance long-term taconite byproduct usage for transportation infrastructure projects, particularly for markets outside of Minnesota where there has been no prior experience working with these materials. This entails obtaining the necessary agency approval for construction purposes, certification and acceptance of the material as a premier aggregate resource with certifying agencies and within the construction industry, and resolving transportation issues that may exist in bringing the materials to the specific targeted markets.

Demonstration projects will assist in accurately assessing the quality and performance of taconite as a bituminous and concrete aggregate material in terms of its fundamental chemical, physical, and mechanical characteristics. Demonstration activities will also include market development, field consulting, manufacturing of the material to pavement specifications, and the development of thorough testing and evaluation protocols, as well as identifying transportation and materials transfer options and procuring the sites needed for storage of the material near demonstration locations.

The project's first out-of-state demonstration occurred in the state of Colorado. A friction course using coarse taconite tailings (fine aggregate) was applied to two bridge decks near Frisco, CO, in May and June of 2006 (fig. 18). NRRI-CMRL prepared over 10 tons of appropriately-sized material for Superior Coating Specialists (SCS) of Proctor, MN.

Coarse taconite tailings are produced continuously by the taconite operations, and their typical gradation (fig. 19) and angularity (100% fractured faces) shows that they can be a ready source of quality material for a variety of fine aggregate (FA) applications, including friction courses, drainable granular fill (fig. 20), and Superpave mix designs.

Additional field demonstration projects are in the planning stages. For example, a major paving demonstration in the Chicago area is being arranged with the state of Illinois, using several thousand tons of Minnesota taconite materials.

Figure 18. Fine taconite aggregate being applied as a friction coarse to a Frisco, CO, bridge deck in May, 2006 (photo source: Superior Coating Specialists, Proctor, MN).

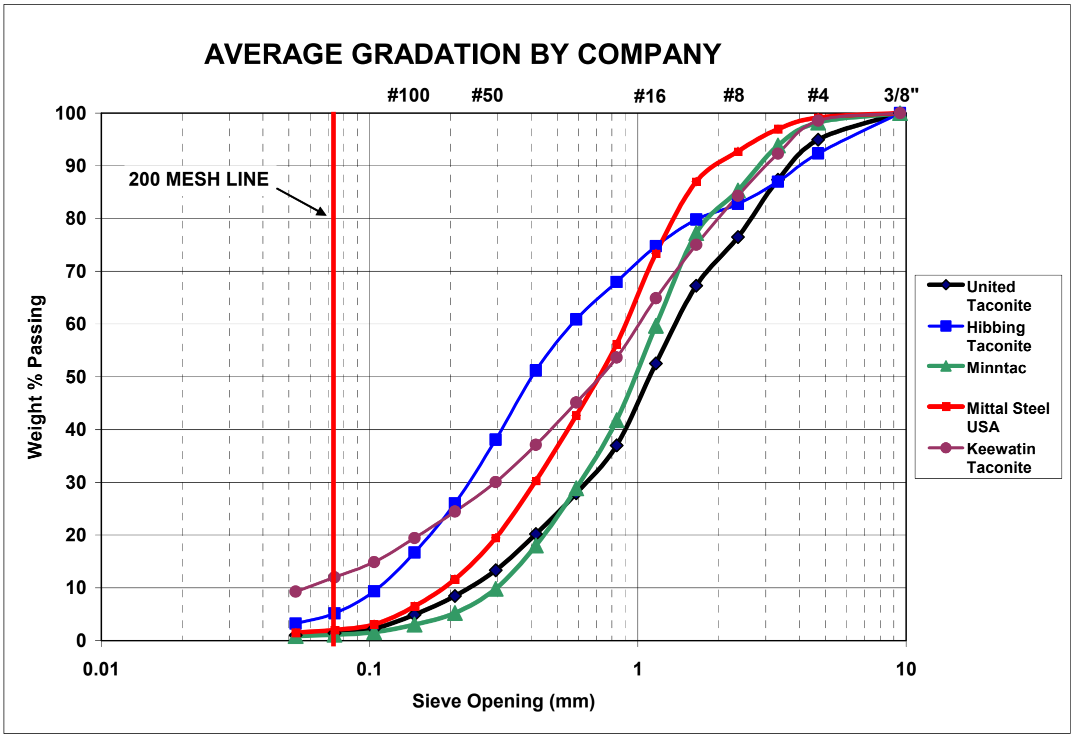

Figure 19. Typical coarse taconite tailings gradation (modified from Zanko et al., 2003b).

Figure 20. Coarse taconite tailings used as granular fill, U.S. Highway 53/169 interchange project (photo courtesy Kurt Johnson, NRRI).

Transportation Logistics and Economics

One of the basic limiting factors in expanding the use of taconite byproducts is the cost of bringing the materials to the market locations. The transportation logistics questions associated with creating a huge new market for taconite mining byproducts must be resolved in order to fully implement this opportunity. Throughout the research program there will be a focus on developing various options to move large tonnages of byproduct materials to desired markets in a cost efficient manner using the intermodal transportation options, e.g., rail, barge, and shipping, which exist in the Great Lakes region (fig. 21). That is why continuing input from – and collaboration with – private and public sector transportation researchers and professionals, university researchers, and aggregate and mining industry representatives who specialize in these areas is a significant part of the research effort.

Work to date has highlighted critical transportation and logistics issues that are especially relevant to: a) near-term demonstration projects; and b) long-term taconite aggregate usage. For example, tight equipment availability (especially rail) and higher energy costs, e.g., fuel surcharges, have been identified as near-term challenges.

Figure 21. Great Lakes Shipping routes (source: Michigan State University).

Taconite mines are currently operating at capacity, impacting equipment availability; however, the industry is historically cyclical, so conditions can change. Potential shippers want a long-term (5- to 10-year), large quantity, commitment/contract for moving Mesabi Hard Rock™.

A significant and potentially cost effective shipping option is the Unit Train/Shuttle Train concept. For example, such a shipment to the Twin Cities (Minneapolis/St. Paul) Metro Area would entail:

- 100-110 cars
- Rapid loading at mine and rapid discharge
- One crew-shift move (rapid turnaround)

The bottom line? Based on optimal conditions, the delivered price to the Twin Cities could be $8 to $10 per ton with integrated operation.

Having efficient and cost-effective transportation options available to all aggregate producers – not just taconite producers – will become even more critical as demand pressures increase on existing aggregate resources nationwide.

SUMMARY

The taconite aggregate research program being led by NRRI is scheduled to continue through 2008. The following objectives are expected to be met during – and by the end of – this comprehensive program:

- Clear delineation of markets for taconite byproducts appropriately discussed with potential end-users.
- Qualification of taconite-based products for application in various highway projects in Minnesota and in the Midwest region of the United States.
- Identification of transportation logistic needs for moving various aggregate products to the identified markets and development of action plans required to meet these needs.
- Development and testing of mix designs for using taconite aggregate products in hot mix asphalt and concrete applications.
- Development and testing of special niche applications for taconite aggregates in road construction applications, e.g., microwave deicing.
- Publication of a complete set of physical (aggregate testing and geo-mechanical), chemical, and mineralogical characterization data for taconite industry byproducts that can be compared to "conventional" stone aggregate products. The availability of such a data set will give potential end-users the information they will need for making rational engineering and environmental decisions for using these byproducts as a new source of highway and construction aggregate within their jurisdictions.
- Development of new and/or modification of current aggregate specifications, and certification of new commercial mix designs for hot mix asphalt (HMA) and portland cement concrete (PCC) applications.
- Large-scale field assessment/demonstration and implementation of innovative aggregate products and concepts that use taconite industry byproducts.
- Better definition/quantification of the transportation logistics and economics for moving various aggregate products to identified markets resulting based on the shipment of taconite industry byproducts to the large-scale demonstration sites.

- Successful demonstration of the actual use of taconite aggregate products on a significant scale throughout Minnesota and the Midwest region of the United States in a variety of paving applications.
- Publication of a final report, and presentation of the research program's findings in trade journals and at public and/or industry forums.

Achieving these objectives will put Minnesota taconite mining byproducts in position for being an important and high-quality source of highway and construction aggregate materials for many markets. Combined with the critical need for repairing, maintaining, and upgrading the nation's transportation infrastructure, the potential for Minnesota Mesabi Hard Rock™ is tremendous.

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Session 4

The Other Side of the Industry

Industrial Minerals Reserves and Resources Classification and Evaluation

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ABSTRACT

The key parts of the definition of a mineral reserve are that it is (a) that part of a deposit that can be recovered and sold (geology, mining, and process engineering), (b) is economically (profitably) extractable (market), and (c) is legally extractable (title and permits), as demonstrated at the time the reserve estimate is made. The classification of mineral reserves and mineral resources from the JORC and similar codes is compared with the SEC's Industry Guide 7, which doesn't recognize the mineral resources categories but does recognize "mineralized material," which is equivalent to the sum of the measured and indicated resources of the JORC and similar codes. The SEC's objection to "resources" stems from the word's similarity to "reserves," the fact that the mining industry's use of these terms is the reverse of common English usage, and that resource estimates allow too much latitude for flights of promotional fancy.

Because reserves are net of mining and processing losses and resources are in-situ estimates, they should not be mixed. Further, because initial estimates of deposit size generally exceed the economically recoverable and saleable quantity, often by a substantial amount, resource estimates, particularly those made early in a projects life, may be misleadingly optimistic.

Both the JORC and similar codes and Industry Guide 7 share some common assumptions. First, they recognize a "blue sky" boundary, a line beyond which estimates of tonnage and grade are too speculative to meet required degrees of assured existence. However, the location of this boundary varies between classification systems. They also include two assumptions that do not apply to industrial minerals; that geology presents the greatest risk in deposit delineation and evaluation and that if you produce a quantity of product (*e.g.* an ounce of gold or pound of copper) you can sell it. Internationally, there are differing views about whether reserves are part of or separate from the resource base. Defining the boundaries between the categories of resources and reserves conceptually would appear to be a problematic area. In practice, this is seldom the case.

The detail and reliability of the mining, processing, environmental, marketing, and other factors required to support a reserve estimate should be very high. Completed full feasibility (bankable feasibility) or reasonably detailed mine plans covering the extraction of all estimated reserves are required by the SEC. Canadian National Instrument 43-101 has less strict feasibility requirements.

For industrial minerals, while geology is important, obtaining environmentally acceptable operating permits and, especially, obtaining marketing contracts are the key elements in determining whether reserves exist. The increasing difficulty and expense of obtaining operating permits is one of the reasons driving consolidation of the industrial minerals business. The other is the "industrial minerals Catch 22." The "industrial minerals Catch 22" results from the need to

have an operational quarry or pit and associated processing facilities in order to obtain a marketing contract but you can't borrow the money to open a quarry and build the plant without the marketing contract to secure the loan. Because processing generally adds most of an industrial mineral product's sales value and because processing plants are very expensive, the economic viability of property depends on whether a processing plant is available or can be built. This mainly depends on the business cycle. Cement, wallboard, and brick plants are examples.

For industrial minerals, demonstrating that you have a market for your product(s) is the key to demonstrating that you have reserves. Because the cost of transportation on a per ton basis often exceeds the loaded value per ton of the product, the delivered cost to the customer's site, not FOB plant or CIF shipping location, determines market limits for competing supply sources. Slight variations in physical and/or chemical properties of an industrial mineral product can be critical in determining which markets a particular deposit is suited for. The presence of small amounts of a contaminant may prevent a property's exploitation unless an economic method of eliminating the contaminant is found.

At many industrial minerals operations a limited number of crude ore types are blended and processed in several times as many product lines defined by brand name and shipping method (50# bag, tote bag, bulk truck load, etc.). The sold quantity of each of these products varies from year to year. A particular product may be made from different crude ore blends, albeit with differing processing costs and losses. Trying to determine project economic profitability, a requirement for determining that reserves exist, becomes an extremely complex exercise, frequently compounded by internal and external competitive security concerns. The easiest way to cut this Gordian knot is by examining the economic viability of the operation as a whole.

Because of the blending requirements of multiple crude types, there is usually a "driver" crude, the quantities and physical and/or chemical characteristics of which make a significant or critical difference in a project's economic viability. Assuring the availability of the driver crude in required quantities is one of the key goals of mine planning and sequencing.

INTRODUCTION

Agricola (1556, p.217) observed that "the first and principal cause [that mines fail] is that they do not yield metal, or if, for some fathoms, they do bear metal they become barren with depth." Because of this fact, estimation of the amount of metal, or other mineral products, present in a mineral deposit has always been a matter of considerable interest to mining investors. This paper addresses several topics related to the estimation of industrial mineral resources and reserves:

- fundamental concepts in mineral reserve and mineral resource classification systems and definitions, including their biases towards precious and base metals;
- the differences between the mining industry's preferred classification and the US Securities and Exchange Commission's (SEC) Industry Guide 7;
- the application of the principles developed to the estimation of industrial mineral resource and reserve estimates; and
- the evaluation of industrial mineral properties.

Before proceeding, we should remember H.C. Hoover's caution regarding the business of estimation and valuation. "Any value assessed must be a matter of judgment and this judgment based on geological evidence. Geology is not a mathematical science, and to attach money equivalence to forecasts based on such evidence is the most difficult task set for the mining engineer. It is here that his view of geology must differ from that of his financially more irresponsible brother in the science" (Hoover, 1909, p. 21). Models of geologic domains and their boundaries underlie all of our fancy computer models and statistical analyses. If these models are wrong, our estimates will be wrong.

DEFINITION OF "RESERVES" AND CLASSIFICATION SYSTEMS

The SEC's Industry Guide 7 states "A *reserve* is that portion of a mineral deposit which could be economically and legally extracted or produced at the time of the reserve determination." The SEC's definition is the most concise definition of *mineral reserves*. The JORC Code and similar mining industry classification systems' (collectively the mining industry definitions) essentially arrive at the equivalent of the SEC's definitions through a circuitous route that first defines *mineral resources* and then *mineral reserves*.

The key elements of the definition of "mineral reserves," either the SEC's or the mining industry's, are (Abbott, 1997 & 1999):

A mineral reserve is:

- the part of a deposit that can be recovered and sold *(geology and mining & process engineering)*,
- economically (profitably) extractable *(market)*,
- legally extractable *(title & permits)*,
- at the time of determination.

For industrial minerals, economic and legal (permitting) issues usually are far more important than the geologic aspects of a deposit. This contrasts with precious and base metals, for which geology usually is the greatest risk.

Figure 1 illustrates the mining industry's mineral resource and mineral reserve classification system.

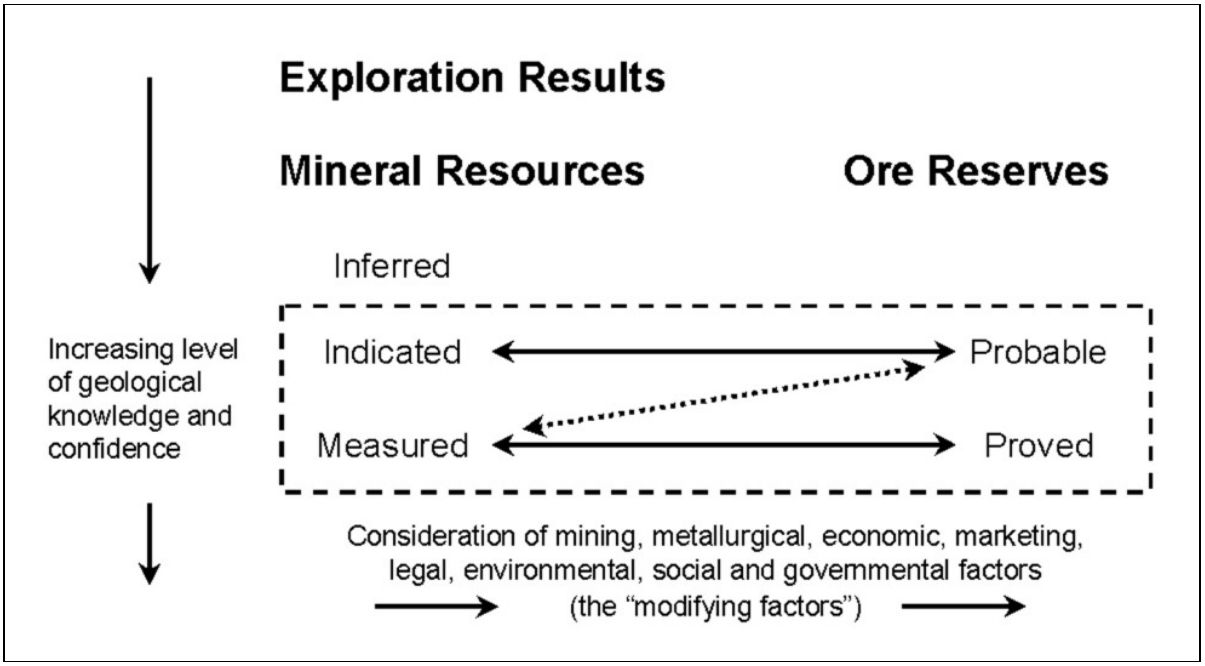

Figure 1. The mining industry's mineral resource and mineral reserve classification scheme based on Figure 1 in those classification systems (JORC Code, 2004; SME Guide, 1999; etc.).

As illustrated in Figure 1, mineral or ore reserves are distinguished from mineral resources by the requirements of the "modifying factors," the factors requiring the profitable and legal requirements of the foregoing key elements of the definition of mineral reserves. Figure 1 also includes the subdivision of mineral resources into the inferred, indicated, and measured categories and of mineral or ore reserves into the probable and proven categories based on the degree of geologic knowledge and confidence in the estimated quantities. While Figure 1's reserves are formally headed "ore reserves," the term "ore reserves" is basically redundant, because "ore" is mostly synonymous with "reserves"; "reserves" is a broader term that includes mineral commodities like coal and some industrial minerals whose economically mineable portions are not generally referred to as "ore." This distinction is pointed out in the note to the definition of "reserves" in the SEC's Industry Guide 7.

The Society of Mining, Metallurgy, and Exploration (1999, paragraph 18) defines *mineral resource* as "a concentration or occurrence of material of intrinsic economic interest in or on the Earth's crust (a deposit) in such form and quantity that there are reasonable prospects for eventual economic extraction. The location, quantity, grade, geological characteristics and continuity of a Mineral Resource are known, estimated or interpreted from specific geological evidence and knowledge. Mineral Resources are sub-divided, in order of increasing geological confidence, into Inferred, Indicated and Measured categories. Portions of a deposit that do not have reasonable prospects for eventual economic extraction must not be included in a Mineral Resource." The note to paragraph 18 states, "The term 'reasonable prospects for eventual economic extraction' implies a judgement (albeit preliminary) by the Competent Person in respect of the technical and economic factors likely to influence the prospect of economic extraction, including the approximate mining parameters. In other words, a Mineral Resource is not an inventory of all mineralization drilled or sampled, regardless of cut-off grade, likely mining dimensions, location or continuity. It is a realistic inventory of mineralization which, under assumed and justifiable technical and economic conditions, might become economically extractable."

The Associated Adjectives: Proven, Probable, Measured, Indicated, and Inferred

The adjectives associated with mineral reserves, *proven* and *probable*, and the adjectives associated with mineral resources, *measured*, *indicated*, and *inferred* are defined in terms of the degree of geologic assurance, as illustrated in Figure 1. The terms *proven* and *probable* were originally defined by Hoover (1909, p. 19).

> Proved Ore: ore where there is practically no risk in failure of continuity.
> Probable Ore: ore where there is some risk, yet warrantable justification for assumption of continuity.
> Prospective Ore: ore which cannot be included in the above classes, nor definitely known or stated in any terms of tonnage.

These were the definitions used by the U.S. Securities and Exchange Commission prior to the adoption of the revised definitions now in Industry Guide 7 (Abbott, 1985, 1999).

The terms used to modify mineral resources, *measured*, *indicated*, and *inferred*, were defined by the U.S. Bureau of Mines and U.S. Geological Survey in their mineral reserve/resource classification (1980) and predecessor publications. These terms were also incorporated into the JORC Code in its earliest editions and from there were adopted by the other mining industry professional societies' guides, including the Society for Mining, Metallurgy, and Exploration's *A Guide for Reporting Exploration Information, Mineral Resources, and Mineral Reserves* (1999).

The basic difference between the adjectives is, as indicated by Hoover's definitions, the degree to which sampling and other data support a degree of geologic assurance with which the mineral deposit being considered is known. The mining industry codes (JORC Code, etc.) modify this degree of geologic assurance approach, which is the basic discriminator, by allowing measured mineral resources to be equivalent to probable mineral reserves if the modifying factors introduce a sufficient level of uncertainty; see Figure 1. For example, if there is uncertainty about how well a proposed processing method will scale up from bench to actual operational size, this may warrant converting a measured mineral resource to a probable mineral reserve.

The definitions used in the guide or code specified for the jurisdiction for which a report is being written (or that selected by the client if a public filing is not contemplated) are the specific definitions that should be used. The amount of sampling and other geologic information required between the various categories, *e.g.* proven and probable, depends on the deposit and the analysis and interpretation of that data. While it would appear at first glance that debates about the appropriate category would be common, in practice they are not. This issue is more fully addressed in the discussion of "Boundary Issues" below.

Common Assumptions in the Mineral Classification Systems

There are three fundamental assumptions inherent in both the mining industry's and the SEC's classification systems;

1. that a "blue sky" boundary exists in each system,
2. that geology represents the greatest risk of failure in the system, and
3. that if you produce a quantity of mineral product, for example, ounces of precious metals or pounds of base metals, the quantity can be sold.

The last two assumptions are not true for industrial minerals.

The "blue sky" boundary in each system represents the boundary beyond which estimates of amount and quality are too speculative to justify quantification. As H.C. Hoover put it in his definition of "prospective ore: "ore which cannot be included in the above classes, nor definitely known or stated in any terms of tonnage" (1909, p. 19). Figure 2 illustrates the "blue sky" boundaries (Abbott, 2001).

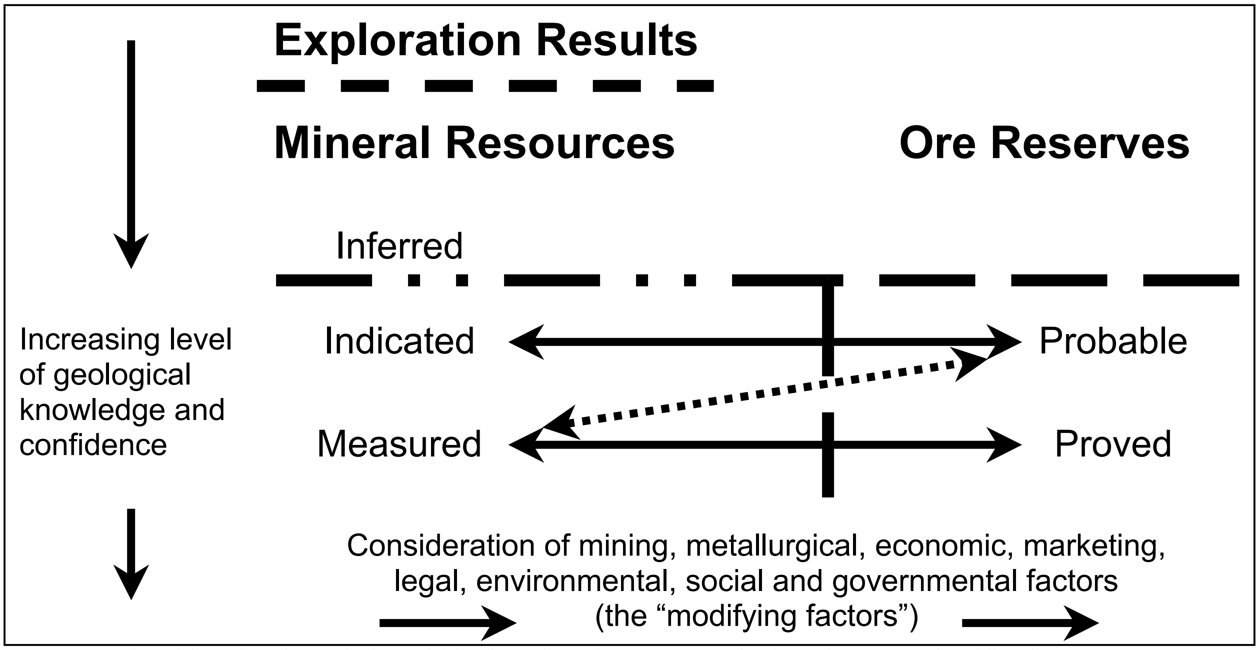

Figure 2. The "blue sky" boundaries within the mineral resource and mineral reserve classification systems.

The boundaries in Figure 2 are between "exploration results" and "inferred mineral resources," between "inferred mineral resources" and "indicated and measured mineral resources," and between "indicated and measured mineral resources" and "probable and proven reserves." The dashed boundary between "exploration results" and "inferred mineral resources" is the mining industry's boundary between the non-quantifiable and quantifiable estimates; "non-quantifiable" being in Hoover's sense that estimates based on this information are too speculative to reasonably or justifiably warrant quantification. The long-dashed boundary around "probable and proven reserves" and separating these categories from the mineral reserve categories is the boundary set in the SEC's Industry Guide 7 between mineral reserve estimates and "mineralized material" estimates. The extension of this boundary separating the "inferred mineral resources" and the "indicated and measured mineral resources" separates the

SEC's"mineralized material" category from the more speculative "inferred mineral resource" category.

There will be further discussion of the differences between the mining industry's and the SEC's approaches to classification later in this paper. At the moment, the topic of discussion is the common assumptions in all classification schemes, of which "blue sky" boundaries is the first.

The second common assumption in mineral resource and mineral reserve classifications is that geologic factors present the greatest risk to the accuracy of the mineral resource and mineral reserve estimates. This assumption is true for metallic deposits but is not true for coal[1] and for most industrial minerals—the precious and semi-precious gems and minerals in pegmatites, hydrothermal vein, and diatreme deposits are the notable exceptions. Most industrial mineral deposits, like limestones, marbles, dimension stones, clays, aggregates, and many others, are geologically relatively simple and exhibit far more consistency of quality over both thickness and along strike than is true of almost all metallic deposits. Indeed the existence of a very large quantity of material that meets minimum specifications is required for most industrial mineral deposits to be considered for economic extraction.

The third basic assumption in mineral resource and mineral reserve classifications is that if you produce a quantity of mineral product, for example, ounces of precious metals or pounds of base metals, the quantity can be sold. While it is true that the price of a metal can vary, sometimes by significant amounts, over a period of days or months, the fact remains that the quantity of metal can be sold at some price whenever it is offered for sale and in the amount offered by the mining firm. Nor does the location of the deposit affect the marketability of metal. Gold or copper produced anywhere in the world can be sold in the appropriate metals market. Again, for the most industrial minerals this assumption does not hold. Delineation of an industrial mineral deposit does not mean that the product(s) produced from that deposit can be sold. Even where permitting is assumed, the ability to successfully market the product(s) remains a major stumbling block. The demand for the product(s) is not infinite (the assumption for precious and base metals). The mantra, "Geology is important but marketing is paramount," is a repeated slide in my presentations on industrial mineral resource and mineral reserve classification. It will be repeated in this paper as well, but in a later part of the paper.

Finally, those claiming that mineral resources and/or mineral reserves exist have the burden of proof for demonstrating the validity of their claims. The mining industry classification schemes include a Table 1, which outlines the types of information required to claim that a particular category of mineral resources or mineral reserves exist.

Are Mineral Reserves Part of or Additional to Mineral Resources?

The answer to the question, "Are mineral reserves part of or additional to mineral resources?" is not as simple as it seems. Yet knowing the answer is very important in mineral resource and mineral reserve classification (Abbott, 1999 & 2001). Figure 3 illustrates the issues involved.

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[1] Although coal is primarily used for power generation and in steel making, as illustrated in the centerfold picture of *Coal—a complex natural resource*, US Geological Survey Circular 1143, coal forms the basis for hundreds of chemical compounds, thus making the coal used for these purposes an industrial mineral.

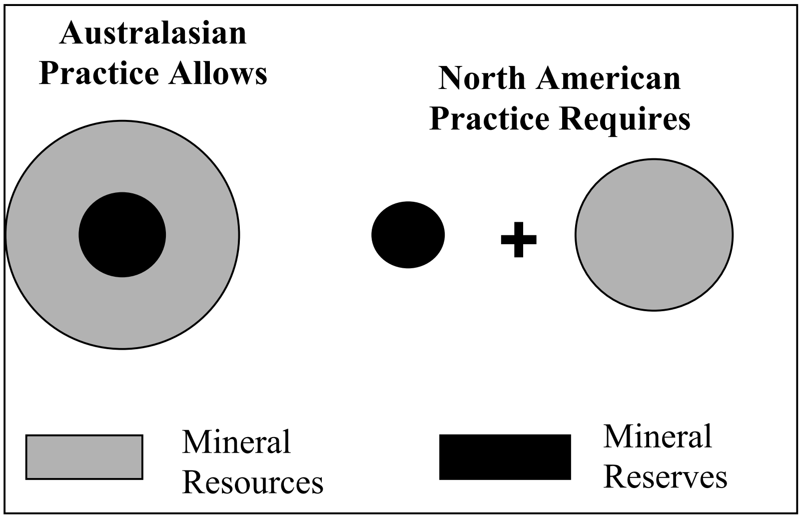

Figure 3. The Australasian and North American answers to the question, "Are mineral reserves part of or additional to mineral resources?"

From one viewpoint, mineral reserves should be part of the total mineral inventory, which includes the associated mineral resources. This viewpoint is accepted in the JORC Code. The problem with this viewpoint is its failure to recognize that mineral resources are estimates of in-situ material while mineral reserves estimates, ultimately, are estimates of the amount of valuable mineral (or is constituent(s) like metals) that can be sold. Thus mineral reserves estimates must be net of all mining and processing losses. They are not in-situ estimates. The mining and processing losses that must be included in a mineral reserve estimate include waste material: the barren, low quality, and weathered zones; physical losses from belts, trucks, loading, pillars, etc.; contaminated material; and processing losses.

The JORC Code optionally allows mineral reserves to be included within mineral resources estimates. It also requires disclosure of whether or not this has been done. North American practice has always separated mineral reserve and mineral resource estimates, recognizing that mixing the two is less like mixing apples and oranges and more like mixing apples and chickens; the two categories are distinctly different.

Because the JORC Code allows the combination of mineral resources and mineral reserves, one must pay attention to reports to make sure whether the Australasian or North American viewpoint has been followed.

Figure 4 illustrates another significant difference between mineral resource estimates and mineral reserves pointed out by Noble (1993). Initial estimates of deposit size increase as drilling continues, reaching a maximum as the limits of the deposit are delineated. This becomes the in-situ mineral resource estimate of the deposit's size, the left-hand column in Figure 4. As mining engineering and processing planning and testing proceeds, particularly as economic constraints are placed on the planning, the size of the deposit decreases. The in-situ mineable estimate, illustrated by the middle column in Figure 4, is the amount of the total in-situ deposit that can be economically extracted. The estimate of greater interest is that of the recoverable amount of valuable mineral(s), shown in the right-hand column of Figure 4. This column is shorter than the in-situ mineable amount due to mining and processing losses. The relative sizes of the three columns in Figure 4 will vary from deposit to deposit. But the size of the three columns will always decrease to the right. Again, the point is that estimates of in-situ deposit size, the mineral resource estimate, are very different from and larger than the estimated amount of recoverable mineral reserves.

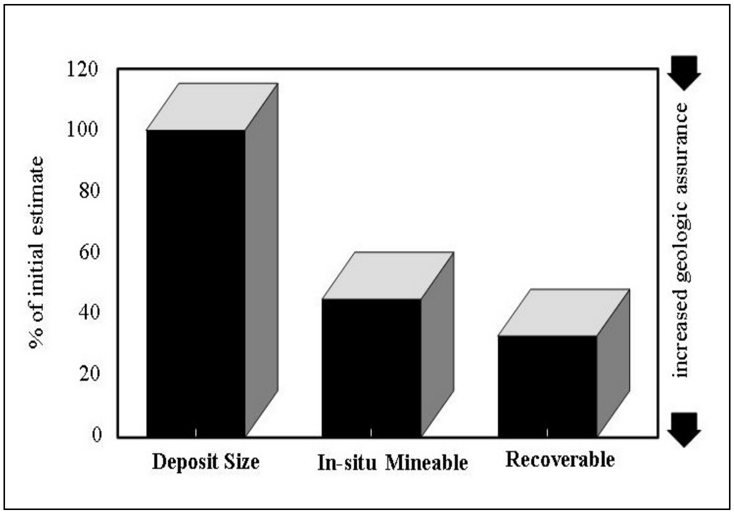

Figure 4. Changes in estimated deposit size as more information is gathered. After Noble, 1993.

Boundary Issues

What is the boundary between one category and another? What characteristics result in a sufficient change in the confidence between one set of estimates and another that results in the first set being classified as an indicated mineral resource and the other being a measured mineral resource? These and similar questions are boundary issues.

When one contemplates diagrams of mineral resource and mineral reserve classifications like those illustrated in Figures 1 and 2, one would expect that boundary issues should present real problems; that deciding which category a particular drill spacing represents should be difficult.

In practice, boundary issues do not present the difficulties one would expect. While there are tests that can be made to determine the adequacy of a particular drill spacing, experienced exploration geologists should have a pretty good feel for the degree of assurance associated by a particular drill spacing simply by determining whether a spacing decrease provides significant amounts of additional information or not. The degree of assurance with a particular drill spacing may vary across the deposit. There may be geologic boundaries such as structural discontinuities, requiring more careful delineation than required for confirming general deposit characteristics away from the discontinuity. While there may be legitimate differences of professional opinion regarding the risk associated with a particular geological or other modifying factor within a classification scheme, they can be resolved with various methods of risk testing.

Reconciliation of estimated versus actually produced quantities provide the best tests of the estimation method used. While reconciliation cannot begin until after mining commences, collecting appropriate reconciliation data should be priority for both confirming estimation methods and for determining whether some problem may be cropping up. Table 1 presents reconciliation data from mining of three different pits within an industrial mineral property.

Table 1. Reconciliation of production data with estimates provides confidence in the estimation methodology.

Percentage of Estimate Divided by Production

Drill Spacing	**Pit 1**	**Pit 2**	**Pit 3**
100-ft/25-ft tons	92.1%	107.5%	100.5%
100-ft/25-ft product	86.3%	102.2%	96.3%
100-ft/actual product	87.7%	-	-

Note: the 100-ft/25-ft spacing indicates that a 100-ft × 100-ft surface drill spacing was followed by 25-ft × 25-ft production drilling after stripping.

The data in Table 1 came from a mining operation that delineated its ore bodies from the surface using a 100-foot × 100-foot grid. After a substantial thickness of overburden was stripped from the ore, a 25-foot × 25-foot grid was drilled for ore control. The "100-ft/actual product" row of Table 1 compares the estimated with the actual amount of product produced based solely on the initial 100-foot × 100-foot grid. Although the calculation method used for the foregoing estimates was simple and done by hand calculator rather than computer modeling, the estimated to actual amounts varied between pits, the accuracy of the estimates was within generally accepted limits. The variation in estimation between pits suggests that the estimates were getting better as more familiarity with the ore bodies was acquired through mining experience.

SEC Objections to the Current Mining Industry Classification Scheme

Although the SEC has traditionally looked to regulated industries, including the mining industry, for technical advice on industry-specific regulations like Industry Guide 7 (Abbott, 1985), industry responses also must recognize that the SEC's primary mission is protection of the public investors in the US, investors who are not sophisticated in the mining industry. The SEC has three primary objections to the current mining industry classification scheme:

1. resource estimates vary widely and are considerably greater than ultimately delineated reserves,
2. the public confuses *resources* and *reserves,* and
3. "resource" estimates allow too much latitude for flights of promotional fancy.

The basis for the first SEC objection, the widely varying resource estimates that exceed ultimately delineated reserves has already been discussed and is illustrated in Figure 4 (Noble, 1993).

The confusion between *resources* and *reserves* is two-fold. First, the two words are very similar and most native speakers of English do not readily distinguish between them without reflection. But even when the difference between the words is recognized, the mining industry uses the reverse of the common English usage, as illustrated in Table 2.

Table 2. Confusion between the words *resources* and *reserves.*

	resources	*reserves*
common usage	available for current use	saved for the future
mining usage	may be available in the future	currently available for mining

The third SEC objection to the mining industry's resources category is based on Hoover (1909), whose definitions of "proven ore" and "probable ore" were originally used by the SEC (Abbott, 1985). While defining these two terms, Hoover observed, "The old terms 'ore in sight' and 'profit in sight' have become of late years subject to much malediction on the part of engineers because these expressions have been so badly abused by the charlatans of mining in attempts to cover the flights of their imaginations. In fact, the substitutes for these terms are becoming abused as much as the originals ever were. All convincing expressions will be misused by somebody" (Hoover, 1909). The SEC's staff is of the opinion that the resource category permits too much latitude for flights of imagination whether fraudulently inspired or not (Abbott, 1997, 1999, & 2001).

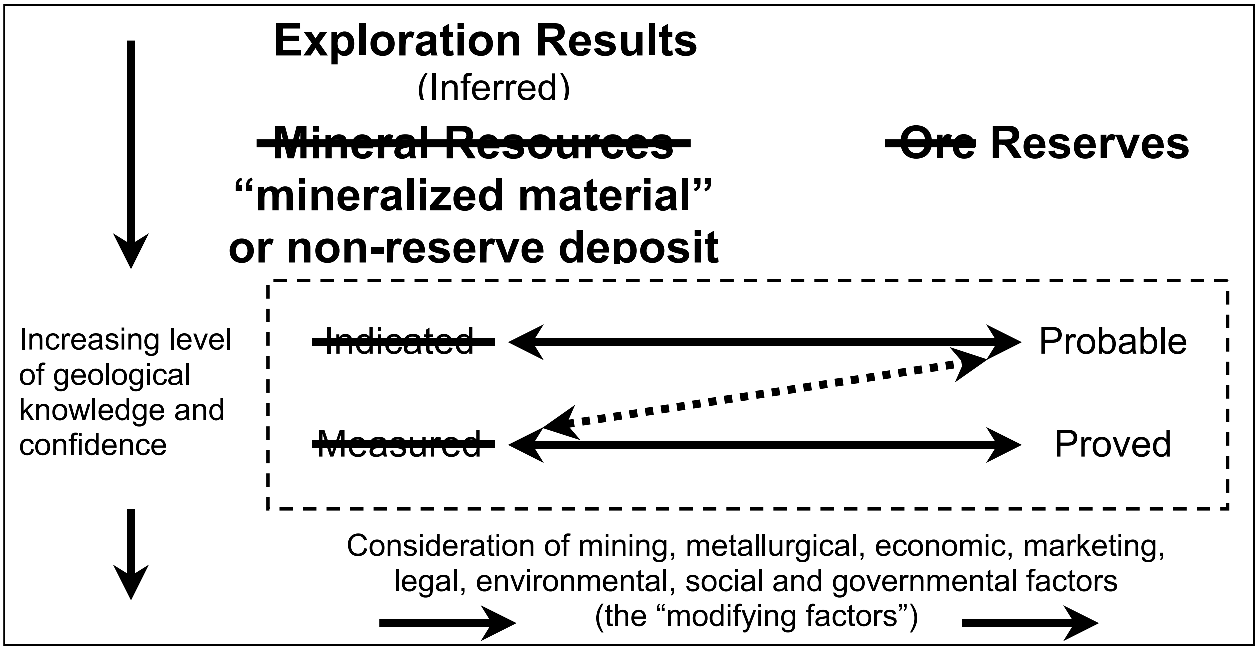

Figure 5. The SEC's mineral reserve classification scheme from Industry Guide 7 and the SEC staff's comments on the use of "mineralized material" for material the mining industry classifies as indicated and measured mineral resources.

Figure 5 illustrates the SEC's current classification system for mining firms using the chart shown in Figure 1. Figure 5 includes the term "mineralized material," which is not found in Industry Guide 7. However, since the later 1990s, the SEC's engineering staff has allowed disclosures of mineralized material through the comment letter process. The standard SEC engineering staff comments on the subject are:

- ♦ In reference to the definition of "deposit", we reserve this term for mineralized material where there has been systematic drilling and other exploration, so that a reasonable estimate of tonnage and economic grade can be made. The use of the term "ore" used in conjunction with the term "deposit" infers the existence of reserves.

- “Mineralized material” is defined as “*a mineralized body which has been delineated by appropriately spaced drilling and/or underground sampling to support a sufficient tonnage and average grade of metals to warrant further exploration. Such a deposit does not qualify as a reserve until a comprehensive evaluation based upon unit cost, grade, recoveries, and other material factors conclude legal and economic feasibility.”* Note that “mineralized material” does not include: 1) material reported as reserves, and 2) volumes and grades estimated by using geologic inference, which are sometimes classed as “inferred” or “possible” by some evaluators. Only mineralization that has been sufficiently sampled at close enough intervals to reasonably assume continuity between samples with the area of influence of the samples can be called “mineralized materials.” Mineralized materials should be reported as “in place” grade and tonnage. Estimates of contained metal or total ounces in mineralized material should not be reported, as these can be confused with reserves.

The SEC’s mineral reserve disclosure scheme can also be presented in a form similar to that used in US Geological Survey (USGS) Circular 831 (1976), known as the “McKelvey box” after the Director of the USGS at the time, as shown in Figure 6.

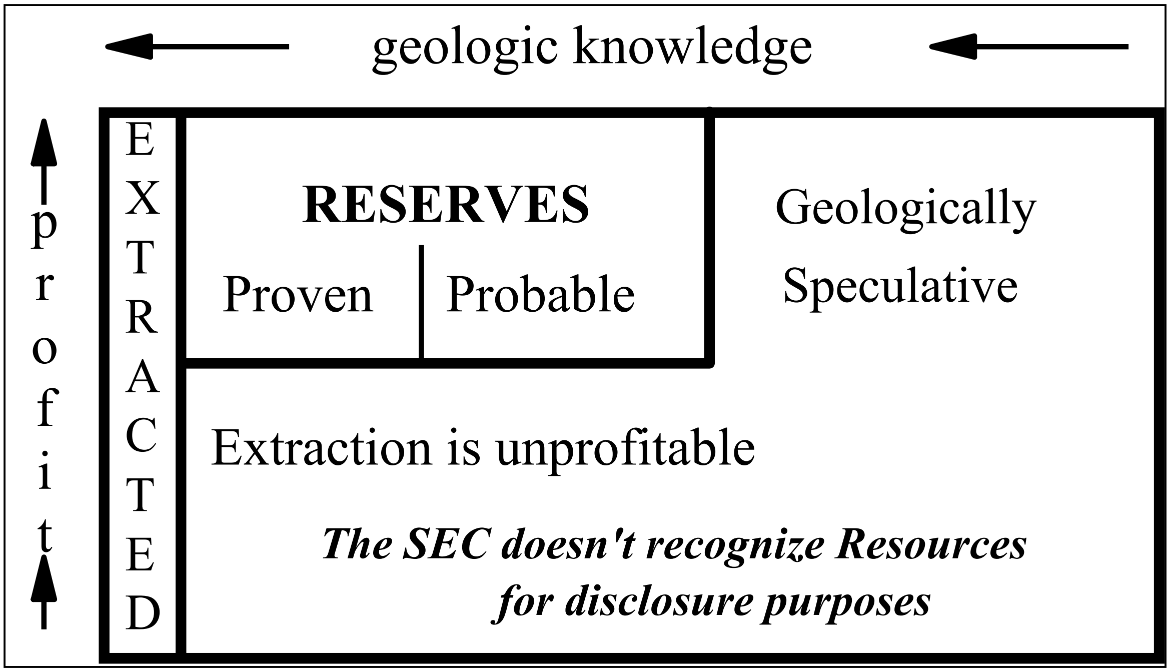

Figure 6. The SEC’s mineral reserve classification scheme in the format of USGS Circular 831 (1976); the “McKelvey box.”

Another SEC requirement that has become increasingly strict in recent years concerns the basis needed for meeting the “economic” or profitably extractable requirement for mineral reserves.

- New mines must have full, bankable feasibility study demonstrating the economic extraction of all claimed proven and probable reserves.[2]
- Operating mines must have reasonably detailed mining plans demonstrating the economic extraction of all claimed proven and probable reserves.

For long-lived industrial minerals mines or quarries (or for a series of quarries feeding a long-lived processing plant), this can present a problem. Identify what will change over time. Usually the haul distance from the quarry to the plant will be the biggest variable. But other variable costs must be considered in the mine planning, for example, variable stripping ratios.

Disclosures about Exploration Information

Although the SEC does not permit quantitative disclosures (tons and grade) about inferred mineral resources, as defined in the mining industry classifications, or about the results of exploration, it does permit and circumstances may even require the disclosure of a good deal of qualitative information, even about exploration information. In the case of *SEC v. Texas Gulf Sulfur* (1966, 1968), which grew out of the discovery of the Kidd Creek deposit and which originally defined illegal insider trading,[3] the initial information found to be material, undisclosed or inside information was exploration information, specifically the results of the first drill hole into a geophysical anomaly. One drill hole, however good (and the first hole into Kidd Creek was very good), is not sufficient to delineate a mineral resource or a mineral reserve even when supported by a geophysical anomaly. One drill hole and an anomaly may give a very good suggestion that a mineral reserve may exist; nevertheless, further drilling, etc. are required (Peters, 1987).

The Kidd Creek discovery was unusual. Most drilling programs proceed with more fits and starts. Yet the property undergoing initial exploration drilling may be the most significant asset of a junior mining company and the exploration of the deposit its only significant business activity. As such, exploration information must be reported. There is actually a great deal that can be qualitatively disclosed without reaching the issue of whether mineral resources or mineral reserves exist. What type of deposit is being explored? What deposit model is being used? Are the results encouraging or discouraging? Are the results prompting a change in plans?

The discovery of the Kidd Creek deposit provides an excellent example of the significance of qualitative information. The results of the initial drill hole at Kidd Creek were known to very few and prompted an immediate and quiet program of additional land acquisition. Following completion of the land acquisition, the drilling program resumed with additional rigs being added at frequent intervals. Unlike the land acquisition program, the drilling campaign could not be kept from the local Timmons, Ontario mining community. An aggressive drilling program is not undertaken unless the results are very good and the project has been moved onto a faster track. Without any hard information on drilling results, rumors of a discovery started simply by observation of drilling activity. This qualitative information led to an increase in the share price of Texas Gulf Sulfur's stock even though no quantitative data had been released by the company.

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[2] Modifiers of feasibility study, such as preliminary, intermediate, and final, are commonly used but have never been well defined. "Full," and "bankable" have always been understood as referring to the final, complete, and thorough feasibility study. This the level of study the SEC staff believes necessary to substantiate a claim that reserves exist.

[3] Other aspects of the Kidd Creek discovery relating to insider trading and the confidentiality of client information are discussed in the chapter on the professional ethics aspects of mineral property evaluation.

The insider trading was committed by the few people who knew something about the actual drilling results. One of the interesting findings in the legal decisions is the finding that there were legitimate corporate reasons for not making the initial drilling results public and for limiting the number of people who knew the details. What was found to be illegal were the trades made by those who had the information prior to its public release and dissemination.

The types of qualitative disclosures about exploration information that can be made include the location of properties being explored, the types of deposit being sought, the plan of exploration, updates on the execution of those plans, whether the results warrant changes in the plans (for example, the rapid increase in the number drill rigs at Kidd Creek), and the general views of the those in charge of the exploration program on the results of the program. None of this information includes the quantitative results of the exploration program. But it does let everyone know what those who are running the program are planning to do, have done, and what they think about the results to date.

Selected disclosure of quantitative exploration information is a potential invitation to a securities fraud lawsuit. The Securities and Exchange Commission's anti-fraud rule, Rule 10b-5 states, "It shall be unlawful for any person, directly or indirectly, by the use of any means or instrumentality of interstate commerce, or of the mails or of any facility of any national securities exchange,

- To employ any device, scheme, or artifice to defraud,
- To make any untrue statement of a material fact or *to omit to state a material fact necessary in order to make the statements made, in the light of the circumstances under which they were made, not misleading*, or
- To engage in any act, practice, or course of business which operates or would operate as a fraud or deceit upon any person,

in connection with the purchase or sale of any security" (17 CFR 240.10b-5).

Mining industry press releases including phrases like "… samples assay as high as …," "… selected samples …," "… ore-grade mineralization …," "… preliminary estimates …," "… near the well-known ___ Mine …," "… along the prolific ___ trend …" all suggest that material information has been omitted and therefore that the disclosures are potentially fraudulent. The reasons for this are that:

- some assay information or sample results are clearly omitted from the disclosure; what about these undisclosed results?
- How can one know what "ore-grade" is for an incompletely explored deposit?
- Proximity to well-known mines or location along a trend, particularly when illustrated by a small-scale map generally suggests unwarranted potential.

What is really needed is the unbiased opinion of those who have examined and analyzed all the data. What do they think, even in qualitative terms? These opinions are what really matters, particularly if rendered by independent observers.

Legally Extractable—Permitting

The legally extractable part of the definition of mineral reserves consists of two major parts: first, owning, leasing, or otherwise having the right to extract the minerals; and second, obtaining the permits required to build and operate a mine or quarry and the associated processing facilities. This second part, obtaining the required building and operating permits, has become the more significant part of legal extractability.

Opposition to mine and quarry permits comes from neighbors, environmental, and other groups for a variety of reasons. The NIMBYs (not in my back yard) and the BANANAs (build absolutely nothing anywhere near anything) are just two common acronyms for opposition. Even those mines, quarries, and processing facilities that use no chemicals face opposition and increasingly lengthy and costly permit application processes.

Common objections to mines and quarries include:

- visual impacts of the operations;
- disturbance of river systems, this particularly affects sand and gravel operations;
- dust and noise, which are part of mining, comminution, and sizing operations;
- truck traffic, particularly for high-volume producers;
- actual or alleged effects on ground water such as a lowered water table and/or contamination; and
- vibration from blasting inducing damage to neighboring structures.

As Sandman (1993) points out, the actual, perceived risk of a project to a community equals the actual hazard plus the public's outrage at the perceived character of the risk. Perceptions may not be realistic, but they drive the outrage and the vehemence driving opposition. Sandman presents strategies for dealing with these problems that a project ignores at its peril.

In order to have a mineral reserve, the required permits must either be in place or there is a firm or reasonably assured basis for believing that the required permits will be issued in due course. The reasonably assured types of un-issued permits are things like certificates of occupancy for buildings under construction. Operating and environmental permits seldom fall in this category.

Terminology Confusion Caused by Geological Surveys and Bureaus of Mines

Geological Surveys and Bureaus of Mines provide a great deal of useful mapping and research information to the mining industry. But when it comes to mineral resources, they add confusion both within the industry and externally in providing information to the general public. This stems from their use of the terms *resources* and *reserves*, and their modifiers *measured*, *indicated*, *inferred*, *proven*, and *probable* for meanings that differ from those discussed above. The mining industry and the SEC agree that mineral reserves are those quantities of minerals that can be profitably extracted under current economic and technologic conditions. But the Geological Surveys and Bureaus of Mines are using these terms in providing the answer to a very different question, namely, what mineral deposits might we be exploiting 25 or 50 or more years in the future? This is a very legitimate question. But it is not the same question as what can be profitably exploited today, the question of interest to the mining industry's investors.

US Bureau of Mines and US Geological Survey bluntly declare their differing use of common terms in the opening two paragraphs of their *Principles of a Resource/Reserve Classification for Minerals* (1976), stating,

> Through the years, geologists, mining engineers, and others operating in the minerals field have used various terms to describe and classify mineral resources,… Some of these terms have gained wide use and acceptance, **although they are not always used with precisely the same meaning**.

> Staff members of the U.S. Bureau of Mines and the U.S. Geological Survey collect information about the quantity and quality of all mineral resources, but **from different perspectives and with different purposes.** *(Emphasis added.)*

As demonstrated by Abbott (2001), no wonder everyone is confused.

COMMON PROBLEMS WITH MINERAL RESERVE ESTIMATES

Prenn (1992) identified a number of common problems with reserve estimates. As applied to industrial minerals, these common problems include the following.

- Sampling errors: are the samples representative of the part of the deposit being sampled? Has appropriate compositing been done? Have the appropriate analytical tests of physical and chemical properties been conducted by qualified labs? Does an appropriate quality control/quality assurance program exist to ensure that analytical results are accurate?
- Geological errors: has the deposit been sufficiently delineated so that no structural or stratigraphic surprises with occur? Have appropriate specific gravity or density tests been conducted—this can be a problem with swelling clays and porous materials like diatomite?
- Modeling errors: has a correct geologic model been chosen for the deposit? Have the relevant geologic boundaries (formation boundaries, facies changes, faults, folds, property boundaries including setbacks, etc.) been included in the model? Have any anisotropies in projection distances been identified? Has the accuracy of the data used in the modeling been verified? Have detailed geologic maps and sections been constructed? Has an appropriate algorithm been used in setting areas of influence? Has the model been tested? How?
- Engineering errors: is the size of the mining equipment appropriate for the amount of material being moved? Have appropriate rock mechanics studies been performed? Can processing bench tests be scaled up to production streams without problems? Why? Is a new process being used? What is the basis for believing it will work? Are there bottlenecks in the mining or processing streams? What is being done to correct them?
- Market evaluation errors: how was market supply and demand estimated? Why will the produced product be able to penetrate the market? Have potential customers used test batches of product to determine whether the product will meet their needs? Does that entity have the working capital required to get the project constructed and running and producing during the market penetration period?

The realities of many industrial minerals projects are that the deposit's geology is frequently very simple; for example, bedded deposits. As a result, the detailed geologic studies common at precious and base metal mines may not exist. However, as Reed (2007) points out, the use of computer models can considerably improve the understanding of a deposit's characteristics and aid in mine planning. Given the extremely simple calculation methods used to calculate mineral resource and mineral reserve quantities, reconciliation of estimated quantities and grades versus actual production is frequently the only way of demonstrating the accuracy of the estimates. If the reconciliation data exists and if the reconciliation demonstrates that the estimates are accurate within acceptable limits, the reconciliation is the best demonstration that the method in use works, as shown in Table 1. Unfortunately, in far too many cases accurate reconciliation data does not exist.

Figure 7 illustrates an example of poor geologic delineation of an industrial mineral reserve. The current and planned pit outlines are shown. The geologic boundaries shown extend to the lower right below the current pit and show the hanging and footwalls of the ore zone along with a footwall border zone. As can be seen by the hanging and footwall boundaries, the deposit has been subjected to some folding. While not shown, there is some drill control on the illustrated section, although the drilling is not that closely spaced. The "reserve" estimate for the ore zone was based on using a block illustrated by the gray block in Figure 7. The height of the block was the bench height and the width of the block perpendicular to the strike was a set amount. The "reserve" estimate was based on the number of bench levels remaining to be mined times the strike length over which the levels would be mined.

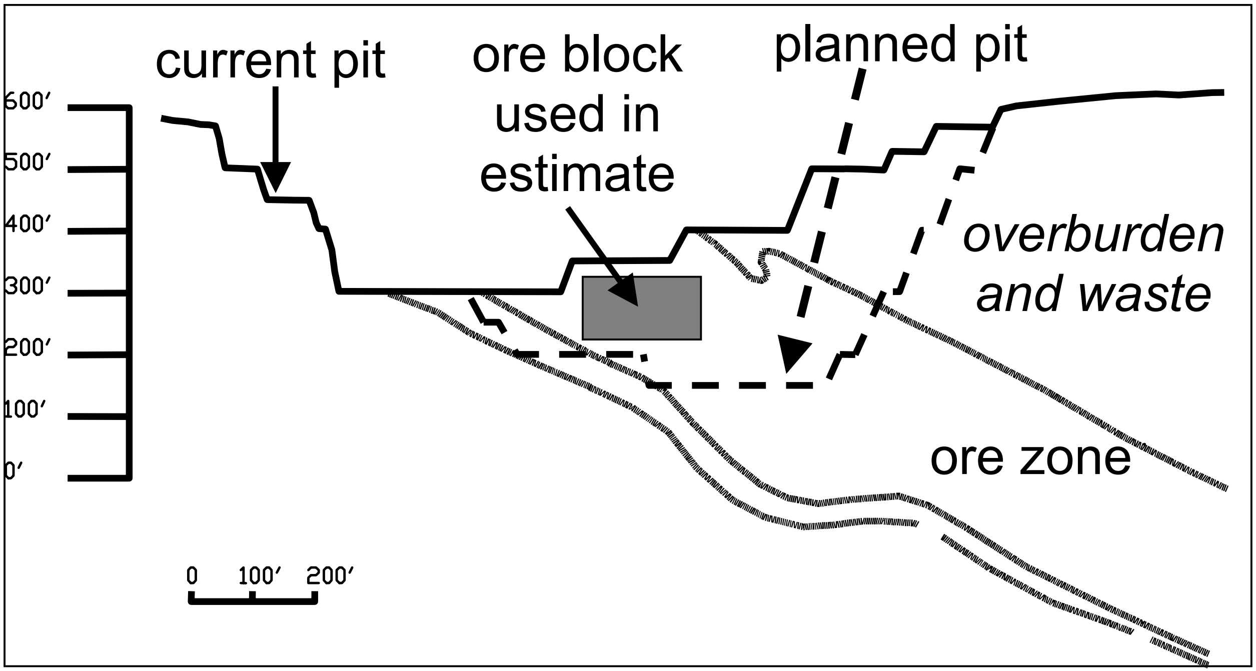

Figure 7. An example of poor geologic delineation of an industrial mineral reserve.

The estimated mineral reserves based on the foregoing methodology clearly existed, but it drastically underestimated the amount of ore present. Because the crude estimation method used was sufficient for several decades of future mining, doing more drilling to more accurately estimate the size of the reserve was not deemed a priority. Then the question arises, why do more? The answer, at least in part, is that with the increasing consolidation of the industrial minerals business into a few large, public companies, securities regulations are requiring stricter compliance with the applicable mineral classification scheme.

The Tonnage Factor

The tonnage factor, the densities of the ore rocks and the gangue rocks, is a vital number in mineral resource and reserve calculations. This is the value (in grams per cubic centimeter = tonnes per cubic meter, or cubic feet per ton), rarely containing more than three significant digits, that converts volume measurements to weight measurements. It is the value whose significant digits, more than any other, limits the significant digits that can be used in the estimates (despite the ability of modern computers to calculate to far greater, but misleading precision). Errors in the tonnage factor determination are multiplied through the whole estimate.

Determining the tonnage factor can be very difficult where the rocks being tested are vuggy and/or contain swelling clays, a common occurrence for many hydrothermal deposits, or are porous like diatomite or perlite deposits. While there are various methods of calculating the tonnage value, one marble quarry, whose royalty owners didn't trust the math, simply had a local dimension stone operation carefully shape and polish a cubic foot of marble, which then could be placed on a scale. Unfortunately, this solution is not always practicable, though perhaps it should be tried more frequently than it is. Variations in the tonnage factor through out the deposit complicate the calculations. Have an appropriate number of samples to test the tonnage factor been collected and properly tested?

Calculating the Cut-off Grade

Cut-off grade is defined as, "The lowest grade of mineralization that qualifies as ore in a given deposit; rock of the lowest assay included in an ore estimate" (American Geological Institute, 1997). Stone and Dunn (2002) provide a fuller definition,

> The grade that will just cover all the costs incurred by (or charged to) the operation is usually referred to as the cut-off grade. In some instances, this figure may include a minimum profit, but for most evaluations it is better to look first at the break-even grade (if for no other reason than to avoid considerations of income tax). Likewise, it is sometimes argued that the developed ore should be treated if it will pay for all subsequent treatment costs, since the sunk development costs are no longer relevant.

Stone and Dunn note at the end of their definition that some argue that material that will pay for the cost of milling should be included in the cut-off grade. Stone and Dunn conclude, "**Unless absolutely unavoidable, ore that will not pay for all of the costs with which it should be charged should never be mined or sent to the mill**" (emphasis in the original). Running sub-cut-off grade material through a mill can only be justified when there is greater mill throughput capacity than delivered ore amounts, and then only when the subgrade material would have to be mined in order to expose ore for extraction. The problem is that running such material can lull an operation into thinking that processing such material is always okay when it clearly adversely affects profitability. Another case is when normally subgrade material is run through the mill is at the peak of a price cycle when the normally subgrade material can be mined and processed at a profit. But even in this case, care should be taken that the overall mine plan and its economic basis are not being unduly compromised.

These definitions are clear but figuring out what an appropriate cut-off grade should be is frequently a more difficult task. Sometimes analysis of the geologic model of the deposit and examination of the analytical data will reveal a natural cut-off grade. Geotechnical characteristics of a deposit may also directly impact the cut-off grade. For example, where the boundary of a geologic domain containing the ore, or located in close proximity to the ore, is a structurally weak zone to which blasting will break during mining, the resulting dilution will impact the cut-off grade that should be used.

Wooller (2001) points out that processing criteria may also affect the cut-off grade. Plant capacity, comminution characteristics (both physical and costs), consumable consumption, and other processing factors can be optimized just like the mine plan.

King (2001) notes that there can be a close correlation between mine production scheduling and the cut-off grade policy. He notes that, "as more of a reserve is mined in a period, the period cut-off grade must increase until the processing and market limits are met. With low [reserve] production rates relative to the mill and market capacities, the cut-off grade would stay on the economic break even grade, referred to as 'mine constrained.'"

Nevertheless, the cut-off grade is ultimately determined by the subtracting the costs of mining, processing, and product sales from the income derived from the product sales. The project economics are tested in a cash flow analysis, with and without assumed discount rates. Prices and costs are normally assumed to be constant unless there is a contractual or other very good reasons for adjusting these parameters. The cut-off grade is the minimum grade required to produce a positive cash flow. But as noted above, the cut-off grade is really dependent on geological, mining, and processing characteristics and so the economic analysis is the last, but necessary step in the analysis. Iterative or optimization analysis is frequently required to select between alternatives.

Arseneau and Roscoe (2000) provide an interesting summary for this discussion of cut-off grade, "It has been [Roscoe Postle Associates'] experience that the main problem in resource estimation does not necessarily lie with the estimation method itself but with the basic application or mis-application of basic geological principles. The main issue revolves around establishing continuity of mineralization and grade within a mineral deposit prior to estimating the resource." Stone and Dunn (2002, p. 114) echo this conclusion, quoting H.M. Parker, "Although there are occasional, and in our opinion 'lucky' exceptions, most successful mining ventures are proven by accumulation of representative short-range data at the feasibility stage by drilling close-spaced holes or from bulk sample pits or underground workings. Conversely, most mines which have been disappointing or have failed because of reserve problems have skipped this step in their development."

Processing—Where the Money Is

Processing is, with rare exceptions, where the money is in industrial minerals projects. The capital and operating costs of the processing plant are frequently far higher than those for mining equipment and extraction. And the value of a ton of material delivered to the processing plant is much lower, often an order of magnitude or more, than the value of a ton of product. However, the minerals in the deposit must be suitable for the processing methods employed. Failures of process flow sheets, failure to identify critical contaminants, failure to pilot plant test, etc. have led to failed projects. Likewise, does one mineral interfere with the processing of another? In some cases, the economic processing of one mineral and the economic processing of a second mineral are less economic than the joint processing of normally sub-economic grade minerals.

These situations are in part responsible for the complex, branching testing of physical and chemical characteristics of an industrial mineral deposit to determine what potential products can be made from the deposit and at what cost. Is a clay suitable for paper or for ceramics? Having made this branch decision, the question becomes which ceramics or which papers? Can a "waste" stream become a saleable product? The dust recovered from crushing and sizing some limestone deposits can be used as a soil amendment. This testing requires larger samples than those normally collected for base and precious metals deposits. The required industrial minerals tests are usually far more complicated than the assaying methods used for metals. The time and costs required for industrial minerals testing is not appreciated by those more familiar with metallic deposits and can lead to significant under-funding of exploration and evaluation programs.

The presence of even small amounts of contaminants can kill and industrial minerals project. For example, fibrous zeolites in an otherwise zeolite-rich deposit can kill the deposit's economic potential because the fibrous zeolites are deemed asbestiform. Likewise the presence of arsenic or mercury in volcanic sulfur deposits can eliminate their cost advantages. The presence of thin seams of halite in a nahcolite deposit can result in failure to meet specification and the loss of large quantities of what were believed to be reserves. Contamination can also occur due to poor mining practices.

Figures 8 and 9 illustrate two different contamination problems. In Figure 8, the dike in a clay deposit near Bovil, Idaho has contaminated the white clay with yellow and red iron oxides forming a waste volume within the deposit. Figure 9 illustrates the failure to cleanly strip the overlying red Amsden Formation from underlying Madison Limestone resulting in Amsden material contaminating the Madison Limestone product.

Figure 8. The yellow dike in this white clay deposit near Bovil, Idaho contaminates the clay with iron oxides creating a waste volume within the clay deposit.

Figure 9. The failure to cleanly strip the overlying red Amsden Formation from underlying Madison Limestone results in Amsden material contaminating the Madison limestone product.

In summary, it must be remembered that a mineral deposit is not an ore body. An ore body is a mineral reserve. A mineral deposit may or may not contain mineral reserves or ore; it will contain material that cannot be mined for various engineering reasons, like pillars in an underground mine, and material than cannot be economically mined, processed, and sold. In the grand scope of industrial mineral project evaluation, geology is important, but permitting and, especially, marketing are more important.

Economically Extractable—Markets

As noted under "Common Assumptions," mineral reserve classification schemes assume that if you can produce a quantity of metal, it can be sold. Therefore, the economically extractable part of the definition of mineral reserves focuses on the cash flow analysis that demonstrates profitability. While such cash flow analyses remain a significant part of the economic analysis for industrial minerals, the far more important question is, can a quantity of product be sold? Is there one or more markets for the product(s) produced, and markets that will purchase product(s) from the proposed operation? Such sales cannot be assumed for most industrial minerals.

The SEC's engineering staff has taken the position in comment letters that in order for an industrial mineral operation to claim that reserves exist, the operation must either have a sustained history of profitable production or have firm sales contracts to purchase the product(s) to be produced. Banks adopt a similar position when deciding whether to finance the construction of an industrial mineral operation. This has led to what I call the "industrial mineral Catch 22," which is illustrated in Figure 10 (Abbott, 1997 & 1999).

Figure 10. The “industrial minerals Catch 22.”

The Catch 22 works like this: in order to have industrial reserves, you have to be able to demonstrate economic viability by having a sales contract. Getting a sales contract requires that you can demonstrate to customers that you can produce the needed quantities of mineral and meet the required specifications. This requires an operating quarry and processing plant. But you can’t get the loan to develop the quarry and build the plant without the sales contract. And so the circle or Catch 22 goes round. This Catch 22 results in the mantra slide I’ve used for many years in lecturing on industrial minerals reserve definitions at the Colorado School of Mines and elsewhere: “Geology is important but marketing is paramount.”

Unlike the markets for precious and base metals, the consumers of industrial minerals tend to represent final- or near-final-stage markets. In many cases the consumer is the end user, or the final processor selling to the end user. For example, the bentonite plants in northeastern Wyoming and adjacent South Dakota sell drill mud and low-end, non-clumping kitty litter as final products to the end user. They also sell by the rail car to companies upgrading the kitty litter by adding other components such as sodium bicarbonate.

Market structure for any particular industrial mineral is based on the competitive market for the end use product. For example, the market structure comparative area for natural trona is global, while the market structure comparative area for road building aggregates has been typically viewed as 25-40 miles in North America (although, for various reasons, this radius may expand significantly in particular markets). Common characteristics of industrial mineral product markets include:

- High producer concentration: generally only a few, well financed firms are able to compete in the market for a particular product. Even in the aggregate and sand and gravel businesses, long the prime example of small, family-owned enterprises, is becoming increasing dominated by a few internationally operating firms. Hence each market is dominated by a monopoly or oligopoly.
- There are virtually no monopsonies or ologopsonies, that is only one or a few consumers of the industrial mineral product, at least in terms of major industrial mineral markets.
- Brand name recognition and strength is one of the things industrial mineral producers strive to achieve in order establish and maintain particular markets. Castle & Cooke's Arm and Hammer brand of sodium bicarbonate is a particularly good example. In another example, World Minerals (now part of Imerys) sells diatomite under the Celite brand name.
- The technical assistance, sales service, and company research and development departments can define market share by identifying particular customer needs and developing a product that meets the required specifications. The differences between many products may be very slight, although these differences may be critical to the customer.
- Due to certain combinations, many successful companies pursue mineral projects servicing similar markets, *e.g.* construction minerals.
- Because the same parent company can produce different industrial minerals products that compete with each other, intra-company secrecy can be as tight as extra-company secrecy. This is an area to which consultants to such firms must be sensitive.

Having the ability to produce high quality commodities does not necessarily result in sales. Sales efforts may fail due to:

- lack of customers,
- total delivered price (product + transportation to the user),
- lack of company history (the brand name issue),
- lack of technical assistance provided to the customer, and
- lack of understanding product specifications.

Marketing and sales strategies for industrial minerals, like those for marketing any product, have short-, medium-, and long-term aspects. Short-term strategies address immediate customer needs, *e.g.* single orders and focus on aspects like product quality, product technical specifications, product deliverability, delivered product price, and beating the competition from similar products. Medium-term strategies are based on competitive bids and historical performance, *e.g.* aggregate bids for road building. Long-term strategies are established by becoming quasi partners with the consumer by not only supplying product(s) with reliable quality meeting the customer's technical specifications, quantity deliverability requirements, and price, but also by working on combined research and development efforts focused on improving existing products or developing new ones. These improved or new products, whether developed in customer partnerships or not, can provide improved or new product competition. Corporate consistency and longevity that provides needed technical support and service, consistently avoids impurity or contamination problems, and possibly providing product substitution also fosters long-term relationships.

Industrial minerals producers are increasingly obtaining ISO certification of their plant(s) and product(s) to improve or maintain their competitive position. Market dominance can be achieved through being the primary supplier in a particular market, or by concentrating on the production of those minerals needed by a selected market, *e.g.* construction materials or paper products. Alternatively, a different type of market dominance can be achieved by being the dominant supplier of a selected industrial mineral with the ability to meet the needs of all customers for that mineral by supplying the mineral products, research and development, technical assistance, dependable service, and reliable deliverability. Either market dominance strategy has the goal of making "price" not an issue for customer orders.

Industrial Mineral Pricing

Due to the chemical- and/or physical-specification nature of industrial mineral products, prices are significantly less volatile than prices for precious and base metals. For many industrial mineral commodities prices have had a near constant growth, commonly at 1% to 3% per year for a number of years. For many industrial mineral products, when managed correctly, the returns are similar to that of an annuity. The ability to generate higher than normal profits tends to be project and/or product specific and not industry-price related. Public company multiples tend to range between 10 and 15 times earnings.

Prices are typically quoted on a FOB plant or CIF shipping location basis. However, the negotiated price is almost always on a delivered cost basis. For many industrial minerals, the cost of transportation exceeds the value of the commodity. This is principally why the market for aggregates has traditionally been limited to a 25-40 mile radius of the processing plant. However, limited deposit availability due to both geologic and permitting constraints combined with existence of "super" quarries located at tidewater or adjacent to main rail lines has significantly altered delivered product costs. Thus tidewater quarries in the Maritime Provinces of Canada or Scotland are successfully delivering aggregate to Florida. Likewise, tidewater quarries in British Columbia are increasingly supplying aggregate to the west coast of the US. Tidewater quarries in Alaska, Maine, and other states cannot compete in this market because of Jones Act requirements for shipping in US-registered vessels. Greek perlite can be delivered to the East Coast of the US at prices that are competitive with domestic production.

Determining the Profitability of an Industrial Mineral Operation

Determining the profitability of an industrial mineral operation, a requirement for determining that reserves exist appears to be a very complicated exercise for two principal reasons. First, one or a few crude ore types are blended in differing proportions and are routed through a variety of processing steps resulting the production of many products. These products can differ in chemical and/or physical specifications. In addition, a single-specification product can be made from different mixes of the available crude types (with differing processing costs and losses). A single-specification product can be shipped in consumer packages, 40- or 50-pound bags, tote bags of various sizes, by bulk truck, and by bulk rail car. Sometimes a single-specification product is sold under different brand names to different customers. Each of these many product and shipping options is sold for a different price and in variable quantities. These variables are schematically illustrated in Figure 11.

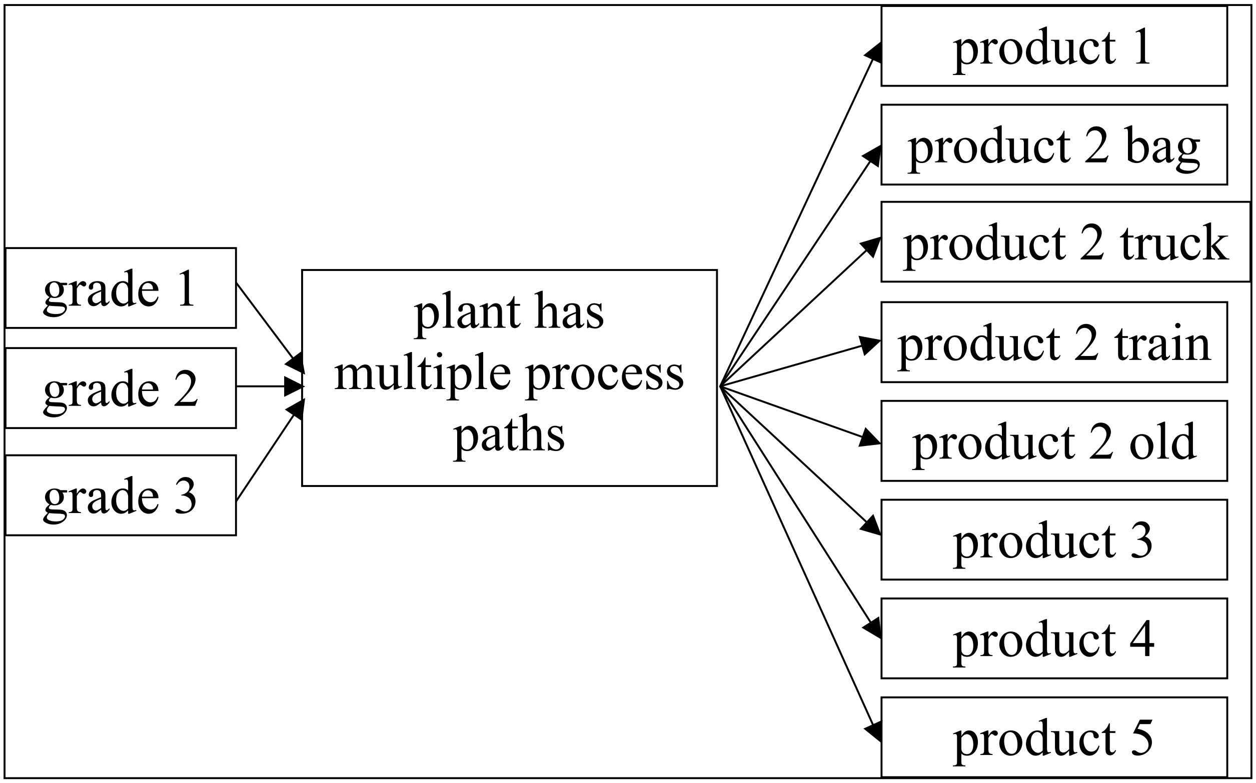

Figure 11. Schematic illustration of an industrial mineral facility in which a limited number of crude ore types or grades are processed into a variety of products.

A second complexity occurs where two or more of the products can compete with each other or with competing products sold by other parts of the same parent company. For example, some perlite and diatomite products can compete in the same filtration or filler markets. Likewise, high-quality and whiteness ground calcium carbonates and kaolins compete in some paper filler and coatings markets. This leads to strict corporate secrecy policies that restrict access to marketing pricing, quantity, and market projection information within parts of the same parent corporation.

In addition, a single-specification product can be made from different mixes of the available crude types with differing processing costs and losses. Some industrial mineral operations have what is known as a "driver" crude. A "driver" crude is the crude type whose quantity and quality are such that its availability for processing makes a significant or critical difference in a project's economic viability. Assuring availability of the driver crude in the quantities required for the planned product mix is a critical part of mine planning and sequencing.

Constructing a matrix accounting for all the variables in crude types, processing stream alternatives, product specification types, packaging and shipping types, and product pricing and quantities can easily become an extremely complex exercise. Behre Dolbear has found that easiest way of cutting this Gordian knot is by examining the operation as whole. All the costs of mining the crude grades and all the processing and packaging costs are summed and compared with the revenue from all product sales. Even when the prices and volumes of particular products vary over time, if the combined operation is profitable over a sustained period, the profitability of the operation is demonstrated and the appropriately delineated crude ore types and quantities can be classified as mineral reserves. The occurrence of an occasional unprofitable year is acceptable if the cumulative sum of profit and losses over a reasonable period of years is profitable.

CONCLUDING SUMMARY

In summary, it must be remembered that a mineral deposit is not an ore body. An ore body is a mineral reserve. A mineral deposit may or may not contain mineral reserves or ore; it will contain material that cannot be mined for various engineering reasons, like pillars in an underground mine, and material that cannot be economically mined, processed, and sold. In the grand scope of industrial mineral project evaluation, geology is important, but permitting and, especially, marketing are more important.

Every industrial mineral operation must answer the following questions.

- What product(s) are being or can be produced? Have the raw material(s) been adequately characterized?
- Market research: does the project understand what and where the markets are?
- Market position: how do(es) the product(s) fit in market place?
- Market penetration: will the project be able to sell into the market; what market share can be reasonably achieved or maintained?
- Processing feasibility: can the project make saleable product(s) in the required quantities on a sustained basis?
- Transportation: can the product(s) get to customers on a price competitive basis?
- Profitability: will the project make a profit selling into a particular market?
- Deposit delineation: does the project have adequate geologic information to estimate tons and quality sufficient to meet specifications?

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Construction Aggregates
Verses
The "Real" Mining Industry

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ABSTRACT

The construction aggregate industry often takes a bad rap…from both the main stream mining industry and professionals alike. Well, I'm tired of the rhetoric and BS and want to set the record straight!

To you mining professionals out there…are you tired of the up and down cyclical nature of the metals industry? Are you tired of working at Home Depot when gold prices are under $300? Well, maybe you need to take a closer look at a part of the mining industry that never goes belly-up! Maybe you need to re-evaluate your preconceptions of construction aggregates! Why? Because that industry is growing more sophisticated, it pays well, it's everywhere, it's social, it's diversified, and it's not in danger of going offshore. And do they really understand that the construction aggregate industry is the largest non-fuel mineral industry in the country?

Often construction aggregates are lumped with the construction industry or sometimes referred to as the "other" mining industry. There are similarities, and there are differences. This paper examines both the technical and social aspects of being in the construction materials industry verses the "real" mining industry. Demand for technical people is increasing as larger companies consolidate the smaller mom and pop operations. The aggregate industry has finally figured out that loader operators maybe are not the best mine geologists. The "other" mining industry may be just the ticket for those who may wish to explore a different lifestyle.

INTRODUCTION

The construction aggregate industry is the largest non-fuel mineral industry in the United States. "Largest" means the aggregate industry is at the top of the pyramid in the amount of products they extract from the earth, or approximately half the volume of all non-fuel material mined. At $15 billion, annual aggregate value in this country dwarfs other non-fuel commodities. The gold mining industry in the United States, the third largest in the world, by the way, only produces $6 billion worth of gold annually. In this country more than 5,000 companies produce sand and gravel and crushed stone from approximately 10,000 pits and quarries. So why is this part of the mining industry, the aggregate industry, treated differently and looked upon with, at best, indifferent tolerance by the rest of the mining industry, or as some would like to say, the "real" mining industry. By the "real mining industry" I mean the metallics…what the majority of Coloradoans and Americans think of when the term mining is spoken. What the majority of members of The Society of Mining, Metallurgy and Exploration (SME) think of when the term "mining" is spoken. And I don't mean the coal mining folks…that's the subject of a whole another paper, those guys are in their separate world as well.

My experience is that both the main stream mining industry and professionals within that industry view aggregates oftentimes as the bastard child or that part of the mining community that is unsophisticated, unlettered, non-professional and unworthy of accolades. Perhaps it's time to set the record straight.

The aggregate industry has matured, they are consolidating, they have become more sophisticated and they realize they need the technical expertise that the "real" mining industry has had for a hundred years.

HISTORY

Before we start into the nitty-gritty of the details maybe we need to reflect on history in order to put the industry in some sort of historical perspective, how did the aggregate industry get started and really….what is it.

The history of mining in this country, especially in the west, is the history of westward expansion. In the 1800s much of the population growth out west was the direct result of prospectors discovering gold, silver and other metals. The California gold rush in 1849 started it all. Subsequently other deposits found throughout the west led to population centers becoming established which in turn resulted in statehood for many of the western territories. Mining created wealth.

Back then mining was the quickest way thought of for the ordinary man to get rich. It turned out to be an allusion for most and the unsavory aspects of human nature often tainted the experience of many. Mining was for gold, silver, and copper…aggregates were yet to be invented! As time passed the mining industry matured and larger, specialized companies sought to extract their riches from the tenacious rock. Mining became a respected industry that supported families and built cities, though sometimes characterized as dangerous; it was none-the-less, a noble profession for some of the far-sighted.

So when did the aggregate mining industry begin? Historically, aggregates have been used since man first started constructing buildings, cities, and roadways. In early history most permanent construction included stone but the Romans were using a form of lime-concrete incorporating broken stone and sand for many of their buildings over 2000 years ago. The construction aggregate industry, as we know it today in the United States, was primarily the result of the need to improve roads. Boston, Massachusetts is reported to have had the first paved streets by the mid 17th century. Most roads in the 19th century were unpaved, but some city roads were paved with wood planks, gravel, cobblestone, brick, or crushed stone, referred to as macadam. In the early 1800s the government appropriated money for the first national highway that eventually extended from the Atlantic seaboard as far as Illinois, and was mostly constructed with broken stone. The railroads then dominated aggregate production in the mid 1800s with their need for railroad ballast (Langer, 1998).

By the late 1800s road improvement was finally recognized as important and the industry as we know it today was born. After the automobile was introduced, in the early 20th century, and became mass produced (putting a theretofore largely immobile populace on the road) the necessity for road improvements and new construction skyrocketed and has yet to subside. The automobile, along with other industrial advancements, changed the lives of ordinary people and increased their standard of living. The aggregate industry is a reflection of that increase in that standard of living over the past century or so. In addition, as technology and science advanced, our homes and places of business developed appetites for new construction techniques and materials including Portland cement concrete, which revolutionized the construction of buildings, homes and roads…all requiring aggregate.

THE DIFFERENCES: AGGREGATE VERSES “REAL” MINING

In order to better understand the aggregate industry one must compare that industry with the classical or “real” mining industry. So what are the differences between the historical view of the “real” mining industry and this relatively new upstart branch of that industry, aggregates? Well, there is not only the obvious differences such as physical properties, price, and socio-economic, but there is also one of attitude. Sometimes these two parts of the mining industry appear to exist in different worlds.

The aggregate industry is part of the mining industry even if they historically haven’t considered themselves as such. The aggregate industry was born of the construction industry. Mining was not the primary focus. The real purpose was to provide crushed rock or sand and gravel for roads and other construction uses. The builders wanted their own sources of material but their main line of business was not mining, it was building roads, or putting the aggregate in concrete or asphalt that went into various construction uses. They didn’t think mining. They associated themselves with construction.

Economic Value—High verses Low

Metal mines produce a valuable commodity that sells by the ounce or pound. Aggregate sells by the ton. There are 2000 pounds per ton. There are 32,000 avoirdupois ounces or 29,166.67 troy ounces per ton. A copper company is lucky if it mines ore that is one percent copper. A gold company is really lucky if it mines ore that is .001 percent gold. Realistically that means they literally throw 99.99999% of all they mine away. Aggregate operators don’t want to throw anything they mine away. It’s a rather poor aggregate operation that wastes 10% of what is mined. In many ways, the tremendous divergence in the value of metals verses aggregates is what drives most all of the other differences between the two.

The low value of aggregate and the tremendous tonnages involved means transportation costs are critically important. Gold can be mined practically anywhere, and transporting the gold, valued at, say $650 per ounce, from Outer Slobovia does not enter into the economic equation. Transporting aggregate, valued at $6.50 per ton, from 30 miles down the road, however, does. Why? Because the price of that aggregate may have just doubled due to the cost of transportation.

In addition, metals can be sold worldwide. Aggregates are generally sold within a certain distance of their end product use, in most cases within probably 30 to 50 miles. Most aggregate is transported by truck on public highways. Depending on state regulations trucks haul anywhere from approximately 20 tons to 40 tons per load. A small, but growing, percentage of total aggregate production is bulk shipped from greater distances.

Physical Property Differences

Metallic deposits are often geologically complicated and detailed mapping and prolific drilling is necessary to outline a potential ore body. Geologists talk of structure, alteration and trace element chemistry. Metallic deposits are limited in their extent to particularly favorable geologic environments, often few and far between. Exploration for metals is literally a world-wide endeavor.

Aggregate deposits geologically are much less complicated. Often it is "what you see is what you get", whether it is sand and gravel or bedrock. Aggregates are a much more common commodity. Mind you they are not everywhere and evaluation is necessary, but it is generally much quicker with less drilling. They are not as hard to find nor as rare as the metallic minerals. The physical properties of the rock are the most important, not the chemistry as in metal deposits.

The size of the operations between the aggregate industry and the "real" mining industry is generally significant, especially with the larger producers in each sector. The larger gold, copper, and other metal mines can be huge, while the largest aggregate operations are relatively small in comparison. Some metal mines can have up to 2,000 employees on site while the largest aggregate operation would be extraordinary if it had 200 people. Some gold operations in Nevada and copper operations in Arizona move in excess of 250,000 tons per day. The vast majority of aggregate operations are relatively small in comparison. A large aggregate operation is in the one million tons per year range. There are even some "mega-quarries" that produce in excess of five million tons per year.

The ore grade dictates between ore and waste in metal mines, and often-times more waste is mined than ore. Incredibly complicated mine models and mining plans are developed to optimize ore extraction and therefore costs. In open pit operations huge equipment is utilized to move the tremendous amounts of material to be excavated. In underground operations shafts sometimes reach several thousand feet in depth. In aggregate operations all the rock is generally considered "ore." There is little waste rock mined, as aggregate operators strive to market even their lower quality material for various uses.

Extracting the metal from rock includes not only crushing but beneficiation by gravity, flotation, leaching, and chemical methods. Processing in the aggregate industry is much more straight forward. They process their material by crushing, screening, and washing. All those nasty chemicals are not needed.

Metals are usually sold by the ounce or the pound in limited quantities. The final product of gold mines can actually be transported by aircraft. Transportation costs for metals to the marketplace do not significantly impact the price. A limited number of large mines world wide can satisfy the demand for metals. Aggregates are sold by the ton in huge quantities. Every city, every county, and every state in this country needs aggregate, and because aggregate is widespread and relatively cheap there are thousands of aggregate mines.

Social Impact Differences

Most metal mines are generally off the beaten path…unless you happen to live in Butte, Montana. Most are remote from major population centers/cities. Large metal mines often spawn their own communities, but those communities are usually small and one-employer towns, certainly not cultural or shopping Meccas.

Aggregate operations are generally as close to population centers as possible, because of transportation costs as related above. In fact, some of the largest aggregate operations are within some of the largest cities in the country. This makes them highly visible to their communities, and especially makes the associated truck traffic that hauls their product, even more visible.

Because metal mines are in rural areas, they are not visible to the vast majority of the population. There is no need for fleets of trucks hauling finished product to market therefore there are no neighborhoods impacted and no traffic congestion.

The mostly rural metals industry reclaims their abandoned operations by primarily recontouring and reseeding. They turn the land back to open space and other multiple use categories. The more urbanized aggregate industry enjoys higher land values and competing land uses. Unsightly open pits are not abandoned, rather secondary uses are found, which may include such things as real estate development (sometimes around lakes that are the result of groundwater filling mined-out resources), flood detention basins, industrial sites, sanitary land fills, water recharge basins, and even golf courses. This sometimes renders the abandoned property even more valuable then it was prior to mining.

Other differences between the “real” mining industry and the aggregate industry include: how they are regulated and permitted, how they are taxed, how federal mining law looks at them, and even what professional organizations represent them. On public lands, mostly in the West, metallic minerals can be acquired using the 1872 Mining Law, which allows the location of mining claims. Aggregates are considered a common variety material, are not locatable, and come under the Saleable Mineral regulations in which a royalty is paid to the government.

THE PERCEPTION

Historically, the “real” mining industry viewed the aggregate industry as being mostly irrelevant to what the “real” mining industry did. The differences as described above are many. The activity of mining was basically the only perceived commonality, but those aggregate guys weren’t real miners. They identified the aggregate industry as small, mom and pop operations. They were generally considered to be unsophisticated with little or no technical expertise or education. These smaller operators learned by “the seat of their pants.” Their equipment was old and was kept together with bailing wire.

The aggregate industry, because it was such a cheap product, was perceived as not being an important commodity and, at that value, aggregates must be everywhere. Anyone could find an aggregate deposit and anyone could mine it. There should be no technical expertise required and certainly one need not have a college degree to know how to mine and process aggregate. What about the business aspects of the aggregate industry? How hard could that be? Since the real” mining industry is not really concerned with marketing their product they probably assumed that the aggregate industry doesn’t need to market their product either. If someone wants some sand and gravel, you sell it to them!

Perception is in the eye of the beholder, however, and what one sees is often through foggy glasses. Let’s look at why the “real” mining industry perception was, and sometimes still is, flawed. The classical mining industry was, in part, inbred. They usually associated with others who were also in the classical mining industry, resulting in a narrow focus that became blinders, strapped to their faces with roof bolts. They were oftentimes far removed from civilization and from the interaction of people and industries outside their profession. If you weren’t a classical miner and if you didn’t think like a classical mine…why then, you weren’t among the chosen!

Why would a professional want to get into the aggregate industry? Probably because it was easy! After all, anyone could dig up sand and gravel and run it over a screen.

I started in the aggregate industry right out of school in the early 1970s. Why? Because I decided I wanted to stay in an urban environment and I wanted to be around a variety of people.

There may have been an influence also, of probably not being the brightest light on the block when it came to interpreting the vagaries of geochemical theory involving spatial relationships of trace elements within alteration hallows of porphyry copper deposits in Arizona. Some of my introverted classmates spent countless hours trying to interpret the latest theories in *Economic Geology* (which I found to be a foreign language publication) while my focus was more, well you might say, all encompassing. I was criticized by one of my previous classmates for choosing such a mundane opportunity as the aggregate industry…I should have aspired to a greater calling!

The "real" mining industry and many of its professionals were the product of a long, albeit honorable tradition of mining, but along the way they may have become a little too cocky and naïve when it came to understanding the aggregate industry. They didn't understand the dynamics, economics, or challenges of the construction and aggregate industries. They were not, and still are not, in the world of marketing their products. They don't have to worry about being competitive. They also don't have to know how that end product is used. They are not as well rounded! Certainly, I am not criticizing them for being an advocate of their professional views, the real mining industry should be proud of their accomplishments and dedication. What I am admonishing is some of the past dismissal, as being below them, or unworthy of accolades, for the aggregate industry.

THE REALITY

The aggregate industry is part of the mining industry. They actually extract (mine) mineral material from the ground and put it to beneficial use. Contrary to what the classical mining industry might think, the aggregate and the "real" mining industry have lots of other things in common as well: geologic input required, mining methods often similar (open pit), mine planning important, permitting required, reclamation required, similar equipment, and similar social/environmental impacts.

In fact, the aggregate industry does a lot better at some things than the "real" mining industry. They are highly visible in their communities. As a result, they are generally more well rounded and more public relations oriented. The transportation issues with the haul trucks are especially impactive to their image. They operate in a real world, urban environment and are probably more acceptable to the general public as the public reluctantly understands the need for aggregate as part of society's daily lives (they just don't want it in their backyard).

They also look at reclamation differently. Productive post mine uses for aggregate operations are more in vogue then for most metal mines because of their proximity to urban areas where land values are higher than in the generally rural environment of the metal operations.

More importantly, the aggregate industry is maturing and is embracing more of the basic technological expertise that has been a part of the "real" mining industry for many years. For instance geological expertise and mine planning is only recently become recognized as an important part of developing an aggregate resource. The larger companies recognize that now and are actively recruiting mining engineering and geology graduates. In the past, they relied mostly on civil engineers if they needed engineering expertise. Civil engineers are more closely aligned with the construction industry, rather than mining. The major companies are now realizing that a mining education background, for their quarry and pit operators, can actually help increase productivity, economics, and quality of the end product.

The aggregate industry is overcoming the "seat of the pants' operations perception of yesterday. They are actually becoming associated with and are cooperating with the classical mining industry, and the classical mining industry is starting to look at the aggregate industry with a little more interest, understanding, and respect. The real mining industry has noticed that a good percentage of new mining engineering graduates are being recruited by the aggregate industry, especially at a critical time when the metals industry is desperate for new mining engineers. They have finally realized that the aggregate industry is bigger than they are, and it is growing more sophisticated.

The construction aggregate industry in the United States today is by far the largest "miner" of raw materials in the country, producing and consuming approximately 3 billion tons of sand and gravel or crushed stone annually, or approximately 10 tons per capita. Every population center in every state, from large cities to small towns, requires construction aggregates for growth, infrastructure maintenance, and literally any type of construction.

Aggregate is used in all concrete, asphalt, roadbeds, public works, commercial construction, and residential construction. Aggregate production over the last few years represents the highest production levels ever recorded in the United States, consistently increasing over the past decade, reflecting the economic vitality of the country's economy.

CONCLUSION –THE CURRENT OPPORTUNITY IN AGGREGATES

So, what about considering the aggregate industry as an option for a career for budding mining engineers and geologists? The demand for technical people in the aggregate industry is skyrocketing as larger companies expand and consolidate the smaller operations. The new and expanding aggregate industry is finally learning that mining expertise and education is important. They are finding out that the old way of doing things does not make as much money in this competitive world as when smart mining is embraced.

The aggregate industry needs engineers, geologists, and other professionals as well. There operations are everywhere. There is no worry about these operations being outsourced to Bangalore. The industry is diverse and vertically integrated, meaning one learns an assorted bag of skills that could be valuable wherever your career path might lead. Vertical integration in the aggregate industry means they not only cover all aspects of the mining industry but also those industries that use the end product. This means concrete, asphalt, construction and construction management. It means all types of construction from housing to commercial, from public works to industrial, from highways to airports, from large to small.

Probably the most important issue that might affect a career choice may be location. A career in the aggregate industry would offer an urban lifestyle practically anywhere of your own choosing. The "real" mining industry can, in no way, offer a similar opportunity. You can decide the amenities of living where you want. Along with an urban environment, would come a social environment of your own choosing. One could be as active as one wants. Family options would also be more available.

So what about you budding geologists and engineers out there who may be just starting along your career path? Do you want to have to:

- Work 24 hrs a day, 10 days on, 4 days off (including travel time)?
- Work at Home Depot when gold prices are under $300?
- Drink alone in a one-horse bar in the boondocks?

- Become a contract worker?
- Wish something you found would actually get mined?
- Be tagged a “consultant” when you can’t find a real employer?

Or….would you like to:

- Have friends?
- Have a real family life?
- Meet someone from the opposite sex that made it through high school?
- Work normal hours?
- Live around other people?
- Live around other people who are really interesting?
- Wear something besides jeans once in a while?
- Have a real life?

Yes, you can have that dream. And the pay is good, there are benefits, there is the opportunity to live in a city where you can have friends, have a family life, get involved with your kids (if you are still married after being gone most of the time). You can learn new and challenging technologies and diversify in a vertically integrated industry.

So, we have learned that the aggregate industry is a formidable entity in this modern world. It has a history, it is huge, it is growing, it has recognition and it has respect.

The aggregate industry has finally figured out that loader operators maybe are not the best mine geologists. The “other” mining industry, meaning aggregate, may be just the ticket for those who may wish to explore a different lifestyle.

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Preventing the Sterilisation of Mineral Resources – Policy, Procedures and Reality in the UK

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ABSTRACT

If mineral resources are fixed and finite, it is sensible and desirable to prevent their unnecessary sterilisation by other permanent development. Sterilisation may occur either by physical development over the resource or by development approaching the boundaries of a resource. The harmful impact of sterilisation extends beyond the immediate impact on a particular mineral deposit because it then diverts extraction pressure to other areas which may be more environmentally sensitive or more distant, increasing both environmental and economic costs.

It has been a requirement of the UK planning process since 1948 that steps are taken by planning authorities to prevent the unnecessary sterilisation of minerals and, if non-mineral development is a priority, to secure prior extraction of mineral. Given the limited area of the UK such an objective is clearly desirable. With the exception of procedures devised for a few minerals of limited outcrop, this has been a bald statement of intent not backed-up by any effective procedures. Subsequent attempts by Government to apply anti-sterilisation policy and procedures more widely may have raised recognition of the issue, but outcomes have remained poor.

The factors leading to this situation include; inadequacies in legislation, ineffective procedures, the pressure for development, lack of understanding of purpose, etc. On the basis that one learns more from ones mistakes than ones successes, this paper will indicate why outcomes have generally been poor to date in the UK, what needs to change, and the relevance of the approach proposed in recent revisions to national mineral policy. However, the will to make a new approach work is going to be the deciding factor. It is uncertain if that will exists particularly when the revised policy has failed to make protection of mineral resources a statutory requirement.

INTRODUCTION

The concern in this paper is not ensuring that an adequate supply of minerals are available to meet demands of society or that mineral and non-mineral development are in principle protected from each other by sufficient stand-off distances. The planning process in the UK satisfies both those issues, although with some degree of uncertainty, dispute, and dissatisfaction. What is of concern are the procedures adopted in the UK to ensure that mineral resources are not sterilised by other development, thereby harming choices of current and future generations.

The possible sterilisation of minerals by development and the success or otherwise of processes to resolve the problem is not just a concern only limited to the UK. It arises across Europe, although with a varying degree of importance, even affecting Norway where, despite the lowest population density on the Continent, urban development is seriously affecting resources of construction and industrial minerals. This is also an issue of concern in Australia, South Africa, China and North America.

The matters discussed in this paper partly reflect contributions to a recent research project on the topic undertaken jointly by the author, the British Geological Survey (BGS), the Quarry Products Association (QPA) and three County authorities, but also reflect long-term involvement of the author in the process. The research was funded by the Aggregates Levy Sustainability Fund. In response to significant problems with existing procedures and with the poor outcomes identified in the research, a guide is being prepared for use by planning authorities, developers and other interested parties on possible methods to improve procedures and provide effective results. The guide will be published by the BGS later this summer. Recent changes in policy for England issued by government in November 2006 are designed to improve outcomes in this area. Those changes have been noted and acknowledged in the guidance being prepared by the BGS. The guidance will shortly be available on the BGS website. The views expressed in this paper are solely those of the author.

THE PROBLEM

There is a 'law' of life that seems to focus development pressure on areas valued for other reasons. One particularly frustrating example is the expansion of urban areas frequently out over valuable and sometimes scarce mineral deposits thereby effectively sterilising those deposits forever. Another 'law' is that which ensures that in the open countryside a pipeline, electrical transmission pylon, or farmhouse is always built right in the centre of valuable mineral deposits.

The economic drivers for the planning authority to allocate land in the urban fringe and for a developer to use urban fringe land for development are readily apparent in many circumstances, yet the knock-on effect is to remove from the resource balance sheet useful materials which have to be replaced in that very development by materials from somewhere else. The provision of the replacement material might involve greater financial cost and could also involve greater cost to the environment either directly or indirectly. That does throw up an anomaly in that despite being in demand, the place value of most industrial and construction minerals is still very low, such that normally any additional costs in bringing in such materials are generally discounted in comparison with other generally significantly higher development costs.

Most cities in the UK are built near rivers and the terrace gravels associated with former river levels provided a flood-free location for those settlements, a source of aggregate to build them, and holes to fill with waste. As the cities expanded, and still expand, pressure on those gravels therefore arises in two directions. First, the continuing demand for aggregate means that the gravels are potentially attractive supply sources to meet that demand. However, that is then countered by the increasing pressure to develop the terrace for various building, etc. uses.

Clearly terrace gravels are very attractive to the building industry. They tend to be flat and well drained, are outside the flood plain, and are easy to dig into to locate foundations or services. In the past worked out gravel pits were often filled with construction and demolition waste plus large quantities of ash from coal fires and many were then subsequently built on. Changes in the constituent properties of waste, the limitations imposed by the Landfill Directive, and incentives to produce recycled aggregate now effectively preclude or prevent filling followed soon by development. This has thereby increased pressure on the terrace gravels which effectively can only be used once instead of potentially providing three assets (aggregate, landfill and built development) as they did in the past.

BACKGROUND TO SAFEGUARDING

The origins of concern about sterilisation of minerals and the procedures adopted to resolve the problem lie with both the enactment of planning legislation in 1948 and concerns about the UK economy. As a principle the planning process was required to seek to prevent the sterilisation of minerals, although there was no mechanism suggested to achieve that desirable objective.

It is perhaps difficult today to understand the economic situation in the UK at that time. Certain materials, particularly steel, suffered from inadequate supply, which caused severe downstream impacts on the whole economy. There were concerns about the supply of a range of minerals, particularly oil, virtually all of which had to be imported at cost to the balance of payments. Action to ensure supply into the future and to prevent the sterilisation of refractory materials (such as silica rock and siliceous clays) of importance in assisting an increase in steel supply was considered necessary.

Similarly, action was deemed necessary to protect future supplies of three minerals, ball clay, celestite and China Clay most of which were exported either as mineral or finished products, earning valuable income to the country. At that time UK ball clay was perhaps the best quality available in the world and supported a substantial UK manufacturing base (tiles, sanitary ware, tableware, electrical porcelain and refractories). The importance of the protection of celestite was significant given that a small area around Bristol provided over 90% of the world's supply and exports earned valuable income.

Pressure for built development over some of these resources was strong and procedures were therefore defined in the early 1950's to protect ball clay, celestite and some other selected mineral resources from sterilisation. This procedure involved the definition of 'mineral consultation areas' where, on receipt of an application for non-mineral development, consultation took place between the planning authorities and the minerals industry to determine if granting consent would sterilise mineral. Sometimes (in say the case of a farmhouse) the development could be relocated elsewhere. Sometimes, evaluation of the site demonstrated that the material was of no commercial value. In a few cases planning consent for the non-mineral development was refused because of sterilisation. However, given that the consultation areas were mainly open countryside, the number of such applications that needed to be considered was few. Basically the process did work and still works well.

In one instance however it may be less effective. The dominance of the UK as a supply of celestite was swept aside by new or enhanced supplies from elsewhere. The UK industry died and died at a time when development pressure was strong such that the consultation process was put to one side ("We don't need to protect current non-commercial minerals do we?") and residential development allowed over part of the resource. It is unclear if this was wise in the context of the needs of future generations, but on the other hand one must be pragmatic. To seek to safeguard all mineral resources would be over protective and undermine the viability of the whole concept.

With the success of these schemes the general concept of a policy objective to prevent the unnecessary sterilisation of any mineral resource then became embodied in planning policy. The problem was that this became nothing more than a statement of intent with no policy teeth and only formalised in relation to a mechanism for consultation and not a policy requirement defining how planning authorities should ensure non-sterilisation.

THE CURRENT APPROACH TO SAFEGUARDING

Given this situation it would perhaps be thought that the UK planning process was actively and effectively ensuring that development avoided mineral resources, such as terrace gravels and others, where possible. After all the UK planning process is all pervasive and very rigorous, the UK is extremely densely populated, mineral resources are fixed, there are significant and widespread constraints inhibiting mineral extraction in a number of areas, and environmental costs of sterilising minerals can be severe.

Unfortunately, except for a few specialist minerals, that has not been the case. Indeed, despite pressure on all resources, and despite the stated ethos that planning is fundamentally about sustainable development, there has, in relation to the majority of mineral resources, been a distinct lack of interest in, or even a blatant disregard of, the need to prevent the unnecessary sterilisation of minerals across all levels of decision making.

This lack of success in mineral safeguarding is well out of balance with the process that applies to almost all other resources or is required to be applied in relation to potential hazards. In the majority of such circumstances the planning process not only seeks to consider the impact but lays down a statutory requirement making such consideration mandatory. Therefore a developer is not surprised, even if he grumbles about cost and delay, if he is required to demonstrate that the building works he proposes does not harm interests such as species, archaeology, soil, water resources, etc. Further he understands that he must demonstrate that his development does not bring occupiers into harm from contaminated land, flooding, mining subsidence, landslides, etc. And in all those respects a developer would normally understand that unless he demonstrates ‘no harm’, with or without mitigation works, then he is unlikely to gain planning permission.

Such factors may cover considerable areas of land in both urban and rural areas and throughout the country. Over half of England is potentially affected by ground stability problems due to karst, mining subsidence, high incidence of landslides, etc. Flooding may affect more limited areas but the issue is of greater significance because of the correlation between expanding urban areas and flood prone areas. Nationally important landscape designations cover over 25% of the country. So, the requirement to take account of such matters is not limited to small individual areas of the country but is widespread. Normally, a developer would have to consider a range of such factors. For example a site near a river valley might involve consideration by the planning authority, when it proposes to allocate land for development, of the impacts of flooding, on high grade agricultural land, on ‘Ancient Woodland’, on potential archaeological remains and on habitats of rare species. The potential developer would need to consider these in detail.

The extent of mineral resources (as opposed to ‘geology’) is no greater than such areas and a requirement to consider safeguarding does not therefore involve some entirely new process over exceptionally extensive area of land and at an onerous level of consideration.

In the processes relevant to other factors, a developer will also normally be required to demonstrate that his proposal has less impact than the development of other sites and may be required to fund extensive and expensive mitigation or rescue works. These may include artefact recovery, the translocation of species, ground stabilising remedial work, surface water management works and so on. Such remedial works will increase site development costs significantly.

The legislative background to this process is stringent. Failure of planning authorities to consult with relevant bodies on such matters would mean that any grant of planning permission could be struck down by the courts. Inadequate weight given to consideration of such factors may also throw doubt on the validity of a permission.

Why has the process to prevent minerals from sterilisation in the UK therefore been so weak to date? Given the widespread practice of consideration of other factors there would appear to be an acceptance in society of the normalcy of both the need to protect resources and the costs involved in that process. And given the professed support for the principles and practice of sustainable development, with its concepts of resource husbanding for future generations, one would expect the approach to minerals to be at least if not more restrictive, precisely because minerals can only be worked where they occur. A number of factors may explain this weakness, but an underlying factor must be the former confused and weak legislative advice and process relating to the prevention of sterilisation.

Association with Extraction

Another important consideration includes the perception that the process effectively is not about resource conservation but about extraction. And given the attitude that mineral extraction is perceived as an undesirable neighbour, there has been resistance to designating areas to safeguard mineral resources. Due to this perception about a link to extraction, there is an indication that planners may have acted to ensure the process is ineffective, or rather may not act at all, thereby helping to preclude extraction and the associated difficult issues that extraction may lead to.

This underlying prospect or threat of extraction, sometimes explicitly stated, sometimes purposely misunderstood, sometimes unfortunately the result of poor advice or safeguarding procedures by authorities (where they only, in effect, safeguarded extensions to quarries), and sometimes a hidden but emotionally powerful agenda of special interest groups, has had a considerable impact in the past. Unfortunately, this perception remains as a major obstacle today, even from decision makers who should know better.

Who Looks After Minerals?

A further major consideration is the fact that there is no government department or NGO in the UK charged with promoting and, importantly in relation to safeguarding, looking after mineral issues. This contrasts with water, agriculture, habitat, etc., where strong advice and comment is issued by the single issue NGO, etc., on the importance of the protection of such resources from development. One might call that advice dispassionate because it comes from technocrats, but it isn't, as it is distorted and elevated by the 'importance' that such people give to the agenda of their agency and the narrowly focussed nature of their objectives and interests.

The Responsibilities of Planning Authorities

In default, safeguarding for minerals is left to planning authorities. Therefore there is no body at national level ensuring that the process works, but only a local body with limited powers subject to the whims of politicians with local interests. More significantly, planning authorities are not charged with promoting the supply of mineral resources for the future but react to requirements laid down by government. Any opinion by a planning authority on the need to protect minerals cannot be determined in isolation and has to be a balanced assessment taking consideration of all other factors. This is a responsibility that does not apply to agencies focussed specifically on ecology, landscape, water, etc. The disadvantage that mineral safeguarding suffers in comparison with other resource factors in relation to its prominence in the wider resource sustainability process is therefore more marked.

A relevant consideration is the structure of planning authorities in the UK. Currently planning authorities are either ‘Two-tier’ (with a ‘County’ authority and a number of ‘District’ authorities within that County, where counties effectively only deal with mineral and waste planning) or Unitary (where a single authority deals with all planning) authorities. As counties have the responsibility for minerals they are advised that they should indicate to districts the areas where they, the counties, wish to be consulted by district councils on applications that might sterilise minerals.

This has not been a statutory requirement until recently, although if advice was issued, the consultation was statutory. Unfortunately, in the past, as the research identified, the advice has often been vague and not followed up when districts failed to comply. Further, districts often ‘lost’ the advisory maps delineating the relevant areas, and appeared to keep on losing them, even when further copies were forwarded. The excuse for such dilatory actions, were as imaginative as the reasons drivers give for speeding. This failure to consider the point seems strange given that district authorities never appeared to lose maps defining other statutory consultations.

It seems even stranger when districts became involved in defining a whole range of rather esoteric ‘issues’ to be considered when determining development applications. In one rural district the planning policy and map showing allocations and constraints failed to consider a policy to protect a strategic mineral from sterilisation (‘failed’ is perhaps the wrong word as the authority specifically took the decision not to refer to the mineral).

However, the authority proposed to designate extensive areas of possible “cold air drainage” problems, where developers would be required to demonstrate that the orientation of buildings would “not cause a significant obstruction to cold air flows resulting in the formation of a cold air pocket” thereby, as seen by the authority, having an impact on energy efficiency and hence a relevant sustainable development criteria. A clear example of not being able to see the wood for the trees and becoming wrapped up in minutiae and ‘fashionable’ issues. The authority had no accurate data to define or evaluate this ‘cold air drainage’ problem. How they proposed to resolve the issue or, of importance, to defend a decision has yet to be resolved.

That does indicate an underlying weakness in planning and sustainability in the UK in that detailed issues tend to run the agenda (‘cold air drainage’, the numbers of one species of animal, the protection of single trees) rather than broad concerns (where are our metal minerals coming from and what is the impact on the environment there).

In unitary authorities the process was even weaker. This was because what advice was given from central government on the prevention of sterilisation discounted the need to show any areas where minerals should be safeguarded and discounted the need for consultation. The lack of consultation was clearly right in so far as it went as there was no specific body to consult with, but seriously flawed in terms of outcomes because it meant that nobody considered the issue at all. Further, given that the relevant areas were often not even identified, there was no formal and consistent way in which the matter would enter into consideration. This has been a major issue because many of the authorities with extensive urban fringes, and therefore with the potential for development pressure leading to the sterilisation of minerals in the urban fringe, are unitary authorities.

The impact of local politicians and politics cannot be disregarded. Mineral safeguarding is essentially about taking a view on issues well into the future, certainly well in excess of 25 years. That lies well beyond the horizon of concern to local politicians whose interest is effectively limited to the next election and their prospects of re-election. Not many politicians are therefore going to stand up and support safeguarding against development, unless that development is controversial. If the development brings employment, or improved infrastructure, or some other desirable asset then in all probability they will put safeguarding aside.

That is not to say that politicians selectively avoid mineral safeguarding, it just means that the objectives of safeguarding just don't feature in their scheme of things. Without strong and clear guidance from national government that position is unlikely to change. Local politics can also influence the process in two-tier authorities particularly where a technical officer in a County seeks to have a non-mineral development, which a District would like to come forward, refused permission due to safeguarding issues. The internal political process can help to quash the technical objection.

CURRENT PROBLEMS WITH SAFEGUARDING

South Wales is the centre of population and business activity in the Principality of Wales. The relationship of limestone, iron ore, refractory minerals (clay and silica), and of coal made the area one of the originating centres of the 'Industrial Revolution', although currently it contains some of the most economically depressed areas in the UK. Unfortunately the price that society in South Wales paid for its contribution to the Industrial Revolution still affects attitudes such that anything to do with minerals is generally considered suspect and undesirable from the start. The area demonstrates the range of problems associated with safeguarding minerals.

While having extensive resources of rock to supply demand today for coarse aggregate for concrete, the area is severely deficient in onshore fine aggregate (sand). Crushed rock fines tend to be harsh, dusty, and cement hungry, not a good thing in a CO_2 aware world. Dune sands found along the coast are too fine grained generally to meet specification for either concreting or mortar sands.

However, for at least the last 60 years, this sand supply problem has been overcome by dredging sand deposits in the Bristol Channel. Currently some 1.1 million tonnes of sand is landed at Newport, Cardiff, and Swansea each year. There is, of course, no 'free lunch' in our actions and concerns about loss of sand from beaches, against a background of perceived rising sea levels from global warming, and offshore impacts on fisheries etc, prompted a review by the Welsh Assembly (the national government body for Wales) of licensing further dredging. The outcome of that review was the decision to seek alternatives to dredging and to protect the limited resources containing sand onshore by defining them as mineral safeguarding areas. That process then identified those resources and the Welsh Assembly has sought, so far with very variable success, to instruct district authorities to designate the safeguarding areas so as to protect the resources for the future when dredging may have to stop.

What happened next fell precisely in line with what a cynical observer of the process might expect to happen. Where the safeguarding areas were in relatively non-sensitive locations (a somewhat limited area of land), the adoption of safeguarding was not resisted. Where however, the areas were in more sensitive locations, such as attractive river valleys or in the Brecon Beacons National Park, objection to the proposed safeguarding arose. In such areas the planning authorities have openly challenged the need to safeguard the sand and gravel resources. Part of the problem has been the link to extraction, noted earlier, and the perception of harm to other resources.

Another part of the problem has been the view expressed by planning authorities, environmental agencies, and decision makers that if land is protected by being in say a protected landscape anyway there is no need for mineral safeguarding. That really doesn't stack up. In practical terms, in the UK planning context just because a mineral deposit may lie in a protected landscape area that doesn't mean that the mineral resource is protected. The landscape protection objection might be overcome with the resulting loss of the mineral resource.

However, the whole approach that minerals can rely on other protection designations is suspect because it conflicts with what happens in the designation of all and every other resource protection consideration. In that process resource protection designations are designated regardless, and with no consideration of the existence of other factors (water quality, habitat, landscape, archaeology, etc). Such factors frequently may overlie each other and do not rely on another designation for protection. The planning process must assess the impact of development on each resource. One is forced to conclude that by seeking to dismiss the need for specific safeguarding for minerals, because of other protective designations, that the agenda of some planning authorities and environmental agencies is not to protect minerals but to protect other resources from possible mineral extraction.

Surprisingly this rejection of safeguarding and hence the rejection of a sustainable approach to resources has been described by environmental pressure groups as a sustainability success. Perhaps one should not really be surprised by that interpretation.

Because of a selective approach to safeguarding deposits, the instruction from the Welsh Assembly has thereby created an inference of extraction, due to the limited nature of the safeguarding areas and the background objective of replacing dredged sand. The reasons why the areas for which protection was sought were not consistently identified and why some significant deposits have been excluded are not known. That has to some extent played into the hands of environmental objectors.

An example of an excluded area can be seen to the east of Newport where the River Ebbw joins the Bristol Channel. Where the river joined the proto Bristol Channel at slightly higher sea levels than today, it deposited a broad terrace of sands and gravels which also filled in relatively deep glacial scour channels cut down into the bedrock during lower sea levels. This deposit extended to some 10 million tonnes in total with the potential to supply about 3 million tonnes of sand for concreting. This is substantially larger than many of the areas safeguarded. However at the same time as the safeguarding process was being promoted, pressure was on to provide land for development for industrial purposes. This area was excluded from safeguarding and part was allocated for industrial use with part of that subsequently developed.

That decision might be justified as a reasoned balance of actions, after all one can't protect every mineral deposit for the future and the development had the prospect of bringing much needed new jobs to the area. However, most of the industrial land has lain vacant for over 12 years, a substantial part of the buildings developed 10 years ago (primarily on the back of European Union and other funds to assist regeneration of economically depressed areas) have never been occupied, and the adjacent agricultural land lies poorly managed. This was a case where prior extraction would have been a practical proposition producing a useful supply of mineral to offset some of the environmental impacts associated with supply elsewhere. Identifying this site as a safeguarded area would have at least prompted people to think about that opportunity and have shown a consistent approach.

The drive to provide safeguarding for sand and gravel was then followed by a requirement from the Welsh Assembly to safeguard other minerals. Unfortunately the basis for the issued advice was so flexible that the outcome has been not only unhelpful to safeguarding but may help to bring the process and concept into further disrepute. This is because it allowed planning authorities to disregard environmentally important areas.

That has been widely interpreted. In one planning authority area, it has effectively created the situation that one of the most important mineral resources has no safeguarding areas, whereas the safeguarding areas for another mineral resource only include a number of thin strips that due to physical and amenity considerations are worthless as safeguarded resources. In another authority it has only focussed on providing a zone around existing quarries. This has become in fact a buffer zone excluding quarrying or development but has failed to protect the resource outside the defined zone.

WILL MINERAL SAFEGUARDING BE ONEROUS – WILL IT WORK IN THE FUTURE?

While safeguarding has been poorly applied in the past there is a desire in government to make a safeguarding process work. That raises issues with the potential practitioners (planning authorities and the development industry) flowing from an uncertainty about the value or effectiveness of the whole process and concerns about workload. Three major issues have often surfaced when discussing this. Those issues are (i) concerns about defining safeguarding areas (ii) the prospect of a 'blizzard' of extra work to take account of the need to evaluate the impact on safeguarded mineral resources, and (iii) explaining the provisions to developers including requiring them to undertake work at cost in both financial and delay terms to demonstrate no harm to the safeguarded resources.

Currently, mineral safeguarding areas are defined on an ad-hoc basis by individual planning authorities. That approach has caused problems, because the areas were defined inconsistently by different authorities. That thereby created an inherent weakness in the process of determining applications which might sterilise minerals. This was because the safeguarded areas may have had irrational boundaries, that were unrelated to resources and that were frequently different at administrative boundaries. As the basis for designation was inconsistent, the strength of policy intervention was also weak and inconsistent.

The approach of some planning authorities in that situation was therefore to minimise conflict and uncertainty by reducing the area of safeguarding to that which, in the majority of circumstances, would not be controversial. In other words, the process retreated from providing the safeguarding it was designed to do. This needs to change, but the old perceptions still remain in the minds of practitioners and the extent of safeguarding areas is therefore an underlying concern in terms of operating the safeguarding process.

One reason why the process was less than successful in the past may have been the illogical nature of guidance on access to maps of safeguarding areas and showing safeguarding areas on development plan documents. Guidance suggested that they should be defined in mineral plans but was silent on their designation in district plans and suggested that they should not be shown in plans prepared by unitary authorities. This was surprising and illogical given that a district or unitary plan was normally the relevant policy document against which development that might sterilise mineral would be determined and was the only development plan document that would normally be taken into account by a developer. If safeguarding maps were available they were not normally directly in the public domain. If the public didn't know about the likelihood of such a map, they didn't ask and therefore were not told. The maps weren't purposely withdrawn from public knowledge but effectively were known only to a few in planning authorities. It is not surprising in such circumstances that their use and the safeguarding process have been ineffective.

District and unitary planning authorities therefore mainly excluded safeguarding areas from their local plans. Guidance then appears to have become interpreted as specifically not requiring designation in local plans. In one district, which contained nationally important industrial minerals, the minerals industry objected to the draft local plan because it excluded the designation of, and a policy on, safeguarding for the industrial mineral. In considering the objection, the inspector at an inquiry specifically discounted the need for a policy and designation, because guidance did not require designation in a district plan. Recent guidance now makes it clear that safeguarding areas and relevant policies must be included in such plans.

An inherent weakness to date has been the inconsistent approach and the drawing of safeguarding areas narrowly. The first solution is to provide a consistent approach that removes bias and provides a degree of certainty to support planning authorities. That situation now prevails given that England is now covered by mineral resource maps prepared by the British Geological Survey, which identify the extent of all mineral resources. Having been prepared by a dispassionate, technically competent body, and not by the planning authority, they should help to provide comfort to planning authorities when used in decisions on safeguarding. Clearly more detailed evaluation of a site may demonstrate that a resource isn't present, but that is a detail to the process. However, the availability of the maps should now dramatically improve designating safeguarding areas and create an effective process in England. Drawing safeguarding areas narrowly falls into the trap of equating safeguarding with extraction and must be avoided.

A major objection to extending mineral safeguarding areas to cover the resource, rather than those areas immediately adjoining a quarry, has been the perception by planning authorities that this would lead to a 'blizzard' of applications requiring consideration. It is not clear why this concern arises. Effectively, most mineral resources will be in the open countryside. Planning policies in relation to development in the open countryside in the UK are already very restrictive. In the urban fringe, the majority of the land will be subject to Green Belt and similar policies, which effectively prohibits development that would remove openness. That excludes built development and the likelihood of a large number of non-mineral development applications requiring consideration will be minimal. Away from urban areas, large swathes of the countryside are subject to international or national conservation designations, which also almost remove the prospect of built development. In the remaining countryside the prospect of gaining consent for built development is also unlikely given general protection policies. It is therefore extremely unlikely that there will be a large number of applications which need consideration if mineral safeguarding areas are designated.

Dealing with the last point, this paper has already noted the scale of factors that a developer is required to consider, and must show as being protected from harm, if he wishes to gain a planning permission. Just because that is already undertaken does not justify in itself a further obligation. However, works to assess ground stability, potential contamination, groundwater levels, etc, are already undertaken both for development and planning reasons. Any additional work to assess the presence of mineral would be small and there is no need for delay if investigation works are planned in parallel. That investigation work might prove the presence of a valuable mineral resource which would need to be protected from sterilisation and therefore the investigation costs by the developer could be seen as wasted money. The same position applies in relation to the investigation of other ground conditions, which generally also are normally always unknown. Such identified ground condition problems may either be resolved by stabilisation works (at substantial cost) or are so expensive to resolve or so uncertain, that the developer walks away from the site.

While the need to protect mineral resources might lead to an unquantifiable reduction in developable land, there is therefore nothing novel or onerous in planning authorities requiring developers to evaluate the presence of other resources and therefore no reason why minerals should be excluded from that process. In terms of financial costs, the assessment of the presence of mineral (one doesn't need to evaluate its commercial potential at this stage) is relatively cheap (5-10%) compared to undertaking an ecological or archaeological evaluation.

Will the process work in the future, or perhaps just work a bit better than it does now? That is unclear, it is hoped that the guide to be issued shortly will assist in both putting safeguarding concerns into context and advising on a consistent approach across the country.

Not a Resource Problem – An Institutional Problem

Natural resource management policy problems have often been described not as problems about resources, but as a problem of the resource management institutions and the attitudes of the people involved. That might be said to be the case with the mineral resource safeguarding issue to date in the UK, where institutions are weak or non-existent and minerals are seen as nasty and not nice, unlike flowers, or birds, or landscape, or old buildings, or bits of Roman pots which everyone wants to protect and where institutions are strong. We, or rather the outcome of the planning process, have been in denial of this inadequate position.

WHAT IS NEEDED TO CHANGE OR STILL NEEDS TO CHANGE

To conclude, the existing process is not effective; changes in process were and are still required and still need to happen. The key points that have had to be addressed or still need to be addressed are:

- Stronger support at national level, not just for the concept but for an effective mechanism.
- Consistent assessment and designation of mineral resource safeguarding designations.
- Ensuring that the same weight is given to mineral resource safeguarding as it given to other safeguarding processes.
- That safeguarding areas are broadly designated in relation to the resource and not narrowly defined and thereby distancing safeguarding from extraction.
- The will to make the process work.

Field Demonstrations of Five Geophysical Methods that Could be Used to Characterize Alluvial Aggregate Deposits

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ABSTRACT

Personnel from the U.S. Geological Survey and Martin Marietta Aggregates, Inc., conducted field demonstrations of five different geophysical methods to show how these methods could be used to characterize deposits of alluvial aggregate. The methods were time-domain electromagnetic sounding, electrical resistivity profiling, *S*-wave reflection profiling, *S*-wave refraction profiling, and *P*-wave refraction profiling. All demonstrations were conducted within a river valley in central Indiana, where the stratigraphy consisted of 1 to 2 m of clay-rich soil, 20 to 35 m of alluvial sand and gravel, 1 to 6 m of clay, and multiple layers of limestone and dolomite. All geophysical methods, except time-domain electromagnetic sounding, provided information about the alluvium that was consistent with the known geology. Time-domain electromagnetic sounding can provide useful information at sites with different geology. All of these geophysical methods compliment traditional methods of geologic characterization such as drilling.

INTRODUCTION

Companies that mine aggregate must know the geology of a deposit to determine whether it can be profitably mined, to select which methods should be used to mine the deposit, and to accurately estimate reserves. The geology of a deposit can be determined, in part, with surface geophysical surveys. For these surveys, instruments on the surface generate signals such as sound waves, radio waves, or electrical currents. These signals are sent into the ground where they interact with geologic heterogeneity. The modified signals return to the ground surface where they are detected and recorded by other instruments. These modified signals are then processed to develop a geophysical cross section of the ground, and this cross section is interpreted in terms of the geology.

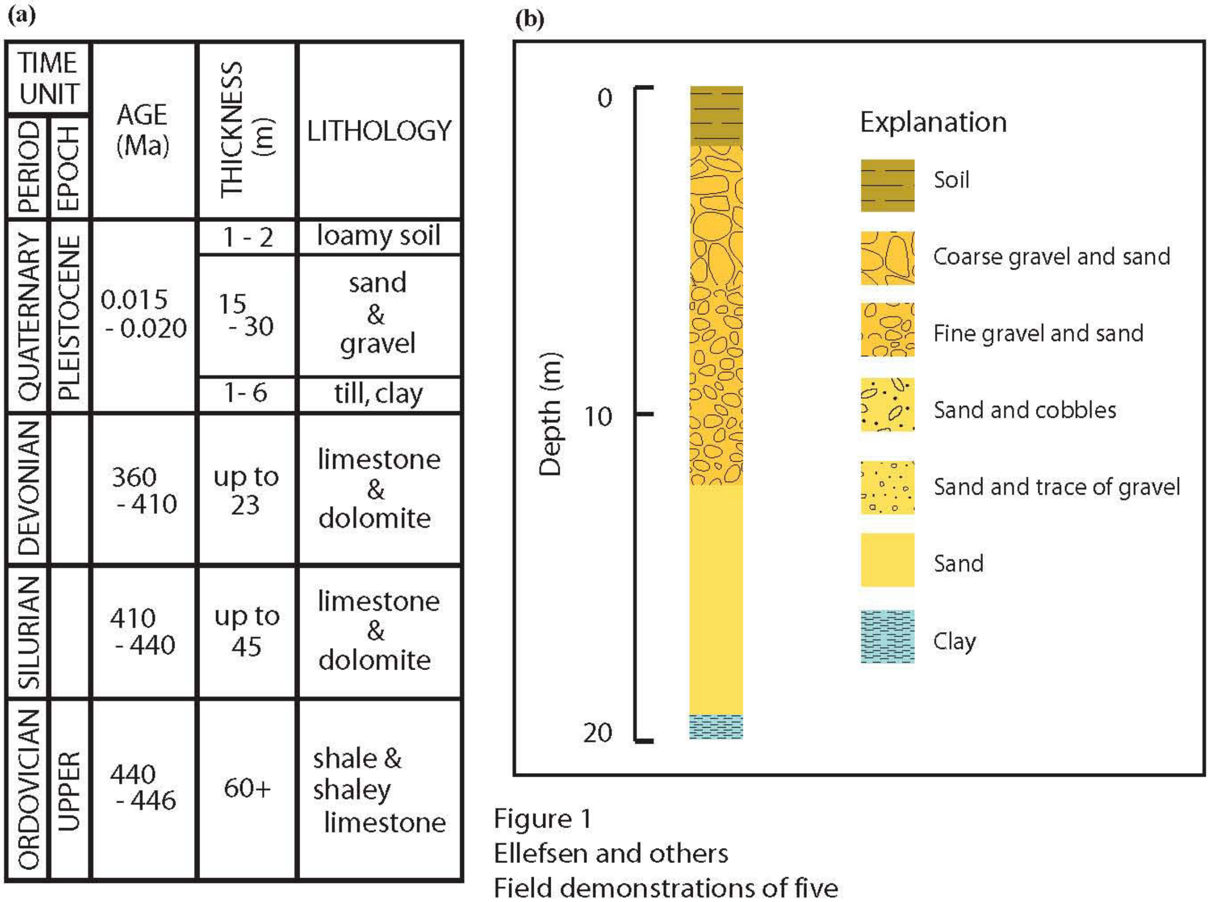
For this study, five different geophysical methods are demonstrated to show how they could characterize an aggregate deposit. The five methods are time-domain electromagnetic sounding, electrical resistivity profiling, *S*-wave reflection profiling, *S*-wave refraction profiling, and *P*-wave refraction profiling. These field demonstrations show the advantages and limitations of the various methods. The article summarizes the results of the field demonstrations; additional information can be found in Burton and others (2007) and Haines and others (2007).

This study involved personnel from both the U.S. Geological Survey and Martin Marietta Aggregates, Inc. The field site for the study was leased for mining by Martin Marietta, and so the exact location of the field site is not stated in this article. Nonetheless, the approximate location of the field site is stated, and the geology of the site is fully described.

DESCRIPTION OF THE FIELD SITE

The field site is near Columbus, Indiana, and is within the Flatrock River valley, which was formed by meltwaters of the Wisconsin Glacier that existed about 15,000 to 20,000 years ago. The stratigraphy pertinent to this study is shown in figure 1a. The bedrock consists of three layers. The bottom layer is shale and shaley limestone of the Upper Ordovician Period, which is 60 m or more thick (Thompson, 1996). The middle layer is limestone and dolomite of the Silurian Period, which is up to 45 m thick (Maier, 2004). The top layer is limestone and dolomite of the Middle Devonian period, which is up to 23 m thick. These layers dip gently to the west into the Illinois Basin tectonic feature (Maier, 2004; Rupp, 1997).

Overlying the bedrock are three layers of unconsolidated sediments (fig. 1a). The deepest of these is a clay layer, which is 1 to 6 m thick (Maier, 2004). The middle layer is alluvium, which is 15 to 30 m thick and mostly consists of sand and gravel. This alluvium is outwash from the Wisconsin Glacier and was deposited mostly as valley train (Indiana University, 2005). The uppermost layer is soil, which is 1 to 2 m thick and is described as silt loam, silty loam, and silty clay loam (National Cooperative Soil Survey, 2002).



(a)

TIME UNIT		AGE (Ma)	THICKNESS (m)	LITHOLOGY
PERIOD	EPOCH			
QUATERNARY	PLEISTOCENE	0.015 - 0.020	1 - 2	loamy soil
			15 - 30	sand & gravel
			1- 6	till, clay
DEVONIAN		360 - 410	up to 23	limestone & dolomite
SILURIAN		410 - 440	up to 45	limestone & dolomite
ORDOVICIAN	UPPER	440 - 446	60+	shale & shaley limestone

(b)

Figure 1
Ellefsen and others
Field demonstrations of five geophysical methods that could be used to characterize alluvial aggregate deposits

Figure 1. (a) Generalized stratigraphic column near the field site (adapted from Indiana University, 1986, and Thompson, 1996). (b) Typical driller's log. The terms "clay," "sand," "gravel," and "cobbles" are taken from the driller's logs, which indicate the sizes of the gravel clasts. In this article, gravel clasts with diameters of about 1 cm (3/8 in) are labeled as "fine gravel"; gravel clasts with diameters of about 1 1/4 cm (1/2 in) and greater are labeled as "coarse gravel."

To determine additional information about the alluvium, it was drilled at 53 locations, and the cuttings were logged. A typical drill log is shown in figure 1b. The lowermost layer is clay, and it is overlain by sand. Analyses of drill logs throughout the site indicate that the thickness of the sand ranges from 4.9 to at least 21.3 m. In some drill holes, the sand is interlayered with sand that includes traces of gravel and sand that includes cobbles. Overlying the sand is fine gravel that includes sand; its thickness ranges from 0.0 to 12.2 m, and the median thickness is 6.1 m. The next layer is coarse gravel that includes sand; its thickness ranges from 3.0 to 11.6 m, and the median thickness is 5.2 m. The uppermost layer is, of course, soil; its thickness ranges from 0.6 to 2.4 m, and the median thickness is 1.2 m. The depths to the water table range from 0.6 to 1.5 m, and the median depth is 1.2 m. Thus, the water table is shallow, and almost all of the alluvium is saturated.

The field site is in farmland, which is practically flat (fig. 2). Because the geophysical data were collected during March, the farm fields were not planted with crops but were littered with parts of corn stalks that had not yet been plowed into the soil. Because neither rain nor snow had fallen recently, the soil in the fields was dry and somewhat hard.

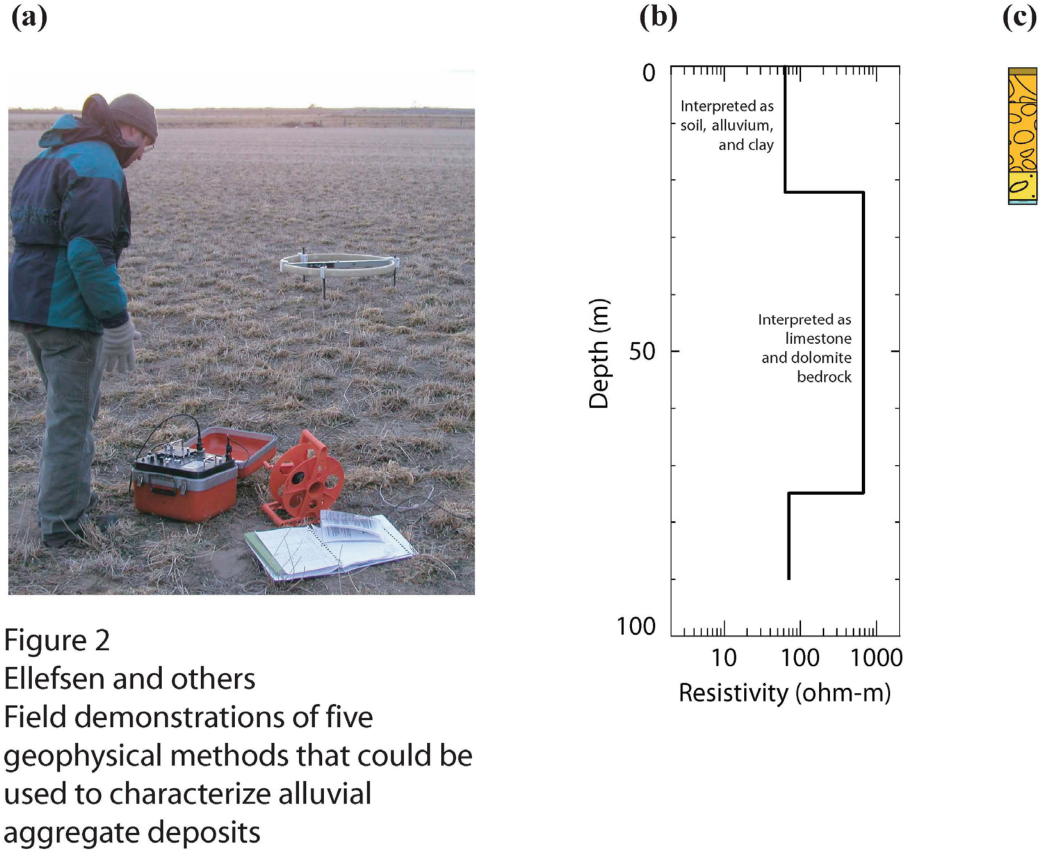


Figure 2. (a) Receiver coil and data recorder used for TEM soundings. (b) Electromagnetic model estimated from a TEM sounding. (c) Driller's log from the hole that is closest to the sounding. The symbols are explained in Figure 1c.

GEOPHYSICAL SURVEYS

Time-Domain Electromagnetic Sounding

Time-domain electromagnetic (TEM) sounding is used to estimate how the electrical conductivity in the ground changes with depth. TEM soundings are typically made using an electrical wire that is laid on the ground in the shape of a square. The wire square conducts a steady electrical current, which is generated by a TEM transmitter. This current, in turn, produces a steady magnetic field. When the transmitter interrupts the current, the magnetic field starts to decay; the rate of decay is affected by the electrical conductivity of the ground. The decay of the magnetic field is monitored with a receiver coil, which is at the center of the wire square (fig. 2a). The receiver coil generates a time-varying voltage, which is called a "transient." This transient contains information on how the conductivity of the ground varies with depth.

The transient is used to estimate the electrical conductivity as a function of depth via a process called "inversion." The model used for the inversion consists of horizontal layers, each of which is parameterized by an electrical resistivity and a thickness. The thicknesses and resistivities for all layers are estimated by the inversion. Additional information about such inversions is in Fitterman and Labson (2005). Results of an inversion are shown in figure 2b. The vertical axis indicates the depth beneath the ground surface. The horizontal axis indicates the electrical resistivity. The model shows three intervals within which the electrical resistivity is constant; for example, the electrical resistivity is about 64 ohm-m between 0 and 22 m depth. Each constant-resisitivity interval corresponds to a horizontal layer in the electromagnetic model. The deepest layer extends to infinite depth. Of course, such a layer is impossible, and so the deepest layer should be interpreted as having a thickness that is too great to be delineated by the TEM sounding.

Figure 2c shows the driller's log from the hole closest to the sounding. The clay layer in the driller's log is close to the clay-bedrock interface because the clay is merely 1 to 6 m thick. The clay-bedrock interface correlates with the interface between the top and the middle layers in the electromagnetic model. The top layer in the model is interpreted as a composite of the soil, alluvium, and clay; the middle layer is interpreted as the limestone and dolomite bedrock (fig. 1a). The favorable result from this sounding is atypical: For most soundings, the clay layer, and hence clay-bedrock interface, correlates poorly with the interface between the top and middle layers in the estimated model. Thus, the TEM soundings at this site did not delineate the stratigraphy as well as expected.

Electrical Resistivity Profiling

Electrical resistivity profiling is used to estimate how the electrical resistivity of the ground changes along and beneath a profile. To measure the electrical resistivity of the ground, direct electrical current is injected into the ground through a metal stake, which is called an "electrode," and the current is extracted with another electrode that is some distance away (fig. 5a). The voltage is measured between two other electrodes that are collinear with the current electrodes. Various orderings of the four electrodes and the spacings between them are used to probe the ground to different depths. To this end, many electrodes (for example, 16 to 100) are alligned, and the spacing between all electrodes is constant (fig. 3b). From this large number of electrodes, a data collection instrument selects four for a single measurement. This instrument rapidly changes the combination of electrodes so that there are measurements for all orderings and spacings. Additional information about the electrical resistivity method is in Zonge and others (2005).

Measurements of voltage are used to estimate the electrical resistivity via an inversion. The inversion is based on a model that is similar to a geologic cross section, except that it displays electrical resistivity. The electrical resistivity may vary within the vertical plane of the model, but not perpendicular to this plane. A typical cross section of electrical resistivity is shown in figure 3c. The vertical axis indicates the elevation, and the horizontal axis indicates the horizontal distance along the ground. The cross section represents a vertical slice through the ground, beneath the line of electrodes. The top of the cross section corresponds to the ground surface. The shape of the cross section is trapezoidal. Only this trapezoidal region was thoroughly probed with electrical current; other regions that were partially probed are not shown. The colors in the cross section indicate the estimated electrical resistivity: The red and orange colors indicate high resistivity; the purple and blue colors indicate low resistivity.

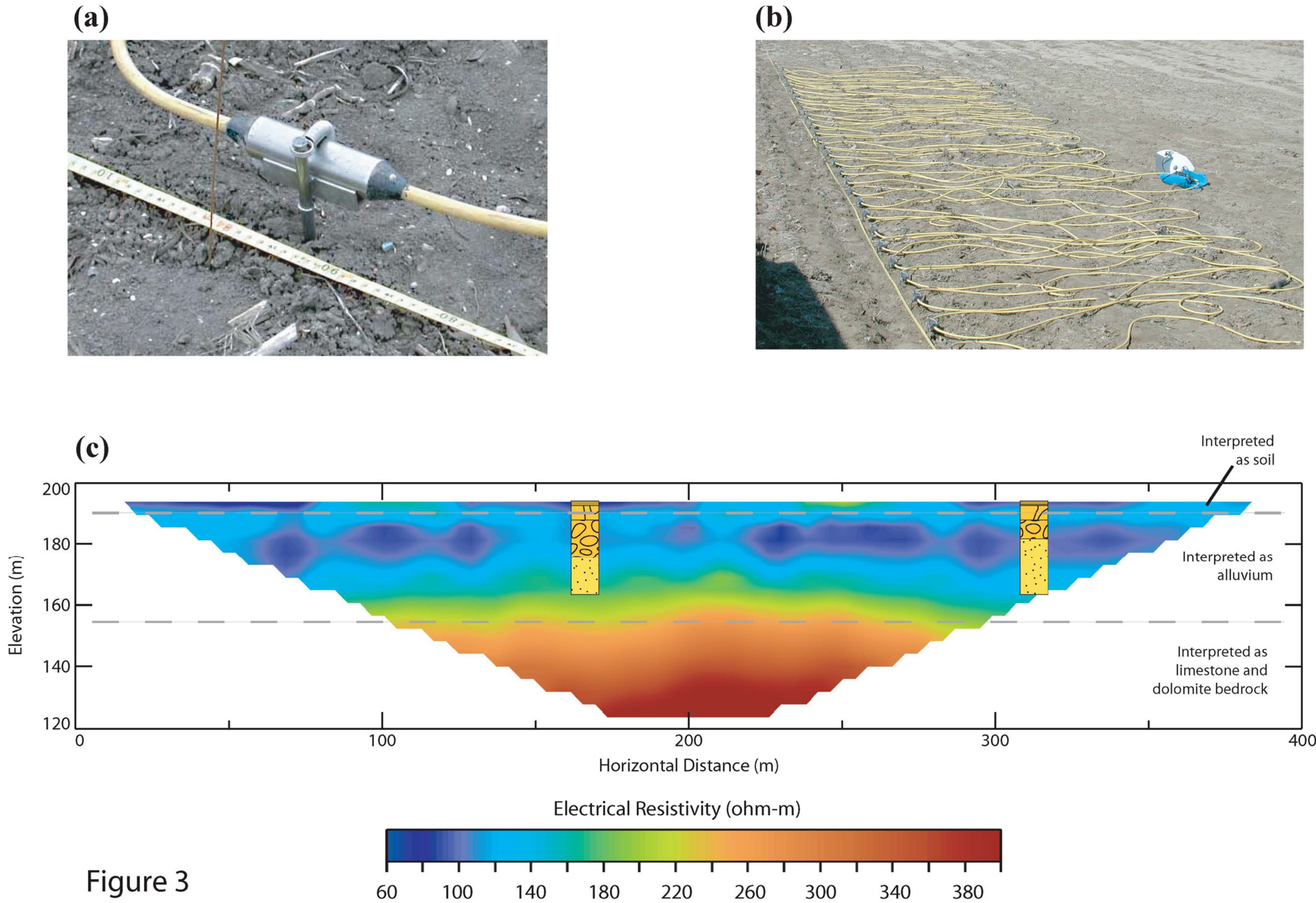


Figure 3
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Figure 3. (a) Electrode and cable attachment used for electrical resistivity profiling. (b) Electrodes and the associated cables used to co one set of measurements. (c) Cross section of electrical resistivity. The symbols in the driller's logs are explained in Figure 1c.

The cross section of electrical resistivity is interpreted in terms of three layers (fig. 3c). The bottom layer extends from 122 m elevation, where the resistivity is greater than 380 ohm-m, to 160 m elevation, where the resistivity is about 220 ohm-m. This bottom layer is interpreted as the Devonian limestone and dolomite (fig. 1a). Within this layer, the resistivity decreases as the elevation increases, perhaps because fracturing and weathering increase. The middle layer extends approximately from 160 to 193 m elevation. This middle layer is interpreted as a composite of the clay, the sand, the fine gravel and sand, and the coarse gravel and sand. The top layer extends approximately from 193 to 194 m elevation, which is the surface of the ground. This top layer is interpreted as soil. Because all profiles of electrical resistivity at this field site yielded cross sections that are consistent with the geology, the method worked well.

S-wave Reflection Profiling

S-wave reflection profiling uses *S*-waves to delineate geologic heterogeneity in the ground. The *S*-waves are generated by a special source that consists of a wooden platform with metal plates on both sides (fig. 4a). One of the metal plates is struck with a small sledgehammer, and the force impulse is transmitted into the ground, generating an *S*-wave. The *S*-wave propagates downwards, reflects from interfaces such as the clay-bedrock interface, and propagates upwards. At the ground surface, the reflected wave is detected by geophones (fig. 4b), each of which generates a time-varying voltage that is digitally recorded. Additional information about reflection profiling is in Pelton (2005).

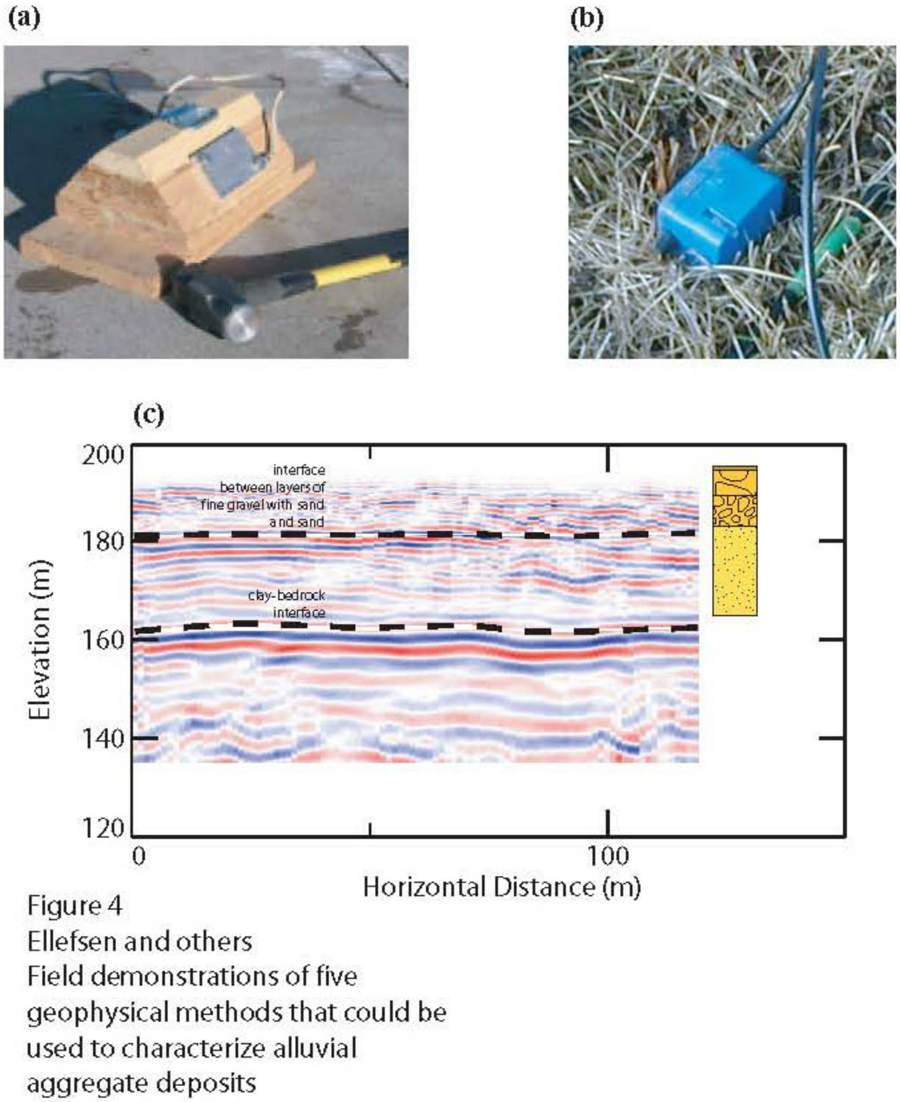

Figure 4. (a) Source that generates *S*-waves for reflection profiling. (b) Geophone that detects *S*-waves. (c) *S*-wave reflection image. The symbols in the driller's logs are explained in Figure 1c.

The time-varying voltages from all geophones are processed with computer software to generate an image of the ground. The image is somewhat similar to a geologic cross section, and its advantage is that it can be readily understood and interpreted. Additional information about this computer processing is in Yilmaz (1987). A typical reflection image is shown in figure 4c. The vertical axis indicates elevation; the horizontal axis indicates the horizontal distance along the ground. The red and blue colors represent positive and negative values in the image.

The reflection image is dominated by two horizontal events. The lower event, whose top is approximately at 160 m elevation, has high amplitude and is coherent across the image. This event is interpreted as the clay-bedrock interface. The upper event, whose top is approximately at 180 m elevation, has moderate amplitude and is partially coherent across the reflection image. This event is interpreted as the interface between the layer of fine gravel and sand and the layer of sand. Because all *S*-wave reflection profiles at the field site yielded cross sections that are consistent with the geology, the method worked well.

S-wave Refraction Profiling

S-wave refraction profiling uses *S*-waves to delineate geologic heterogeneity in the ground. The *S*-waves are generated by a special source that is a heavy steel box with spikes on its bottom, which mechanically couple the steel box to the ground (fig. 5a). The side of the box is struck with a large sledgehammer, and the force impulse is transmitted into the ground, generating an *S*-wave. The *S*-wave propagates downwards, refracts (transmits) from the alluvium into the bedrock, refracts (transmits) from the bedrock into the alluvium, and finally propagates upwards. At the ground surface, the refracted wave is detected by geophones, which are also those used for reflection profiling (fig. 4b). Additional information about *S*-wave refraction profiling is in Ellefsen and others (2005).

The time-varying voltages from all geophones are processed with computer software to generate a cross section showing the *S*-wave velocity. A typical cross section is shown in figure 5b. The vertical axis indicates elevation; the horizontal axis indicates the horizontal distance along the ground. The colors represent the estimated *S*-wave velocity. This cross section is different from that for the *S*-wave reflection profiling (fig. 4c) because the behaviors of the refracted and reflected waves, and hence the processing, are different.

The cross section for the *S*-wave refraction profile (fig. 5b) is interpreted with two layers. In the top layer, the velocities range from 180 m/s at 195 m elevation to 425 m/s at 161 m elevation. This layer is interpreted as a composite of the unconsolidated sediments at the site: the soil, the coarse gravel and sand, the fine gravel and sand, the sand, and the clay. In the bottom layer, which extends from about 150 to 161 m elevation, the velocities are about 2500 m/s. This layer is interpreted as the limestone and dolomite bedrock. Because all *S*-wave refraction profiles at the field site yielded cross sections that are consistent with the geology, the method worked well.

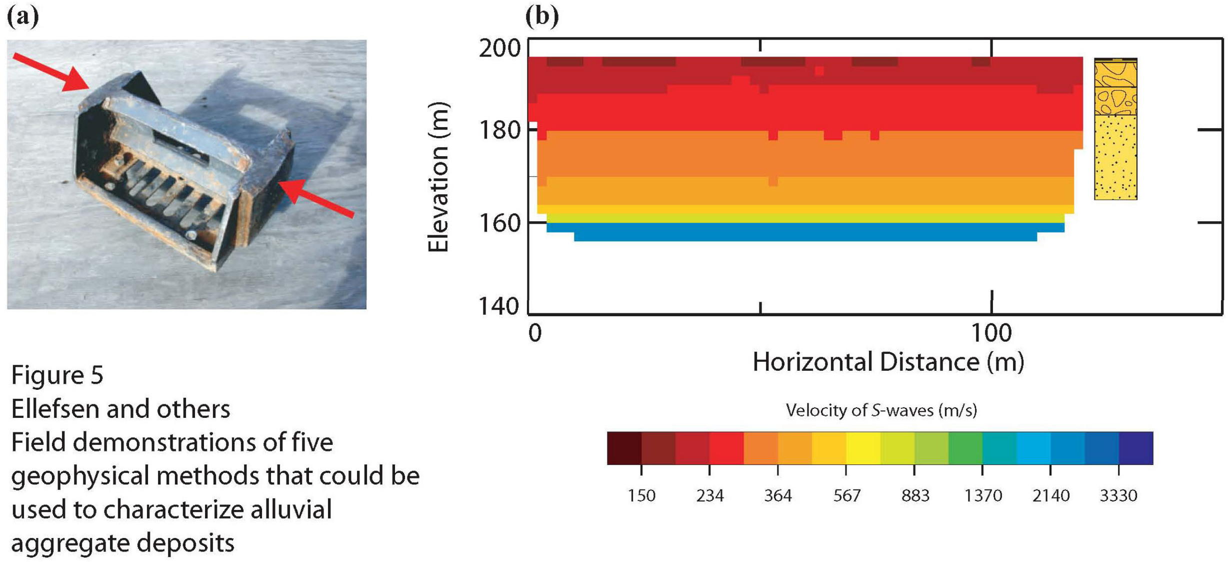

Figure 5. (a) Source that generates *S*-waves for refraction profiling. The arrows indicate where the source is struck by a sledgehammer to generate *S*-waves. (b) Cross section of *S*-wave velocity. The symbols in the driller's logs are explained in Figure 1c.

P-wave Refraction Profiling

P-wave refraction profiling uses *P*-waves to delineate geologic heterogeneity in the ground. The *P*-waves are generated by a source whose principal parts consist of a vertical metal bar, which is mounted on a modified drilling truck, and a metal plate, which is implanted in the ground (fig. 6a and b). When the metal bar is lifted about 2 m off the ground and released, it hits the metal plate, and the force impulse is transmitted into the ground, generating a *P*-wave. The *P*-wave propagates downwards, refracts from the unsaturated alluvium into the saturated alluvium, refracts from the saturated alluvium into the bedrock, refracts from the bedrock into the saturated alluvium, refracts from the saturated alluvium into the unsaturated alluvium, and finally propagates upwards. At the ground surface, the refracted wave is detected by geophones (fig. 6c). Additional information about this method may be found in Pelton (2005).

The processing of *P*-wave refraction data is similar to that for *S*-wave refraction data. Likewise, the cross sections obtained with *P*-wave refraction profiling are similar to those obtained with the *S*-wave refraction profiling. A typical cross section for a *P*-wave refraction profile is shown in figure 6d. The velocities appear as three distinct layers. In the top layer, whose elevation is between 193 and 195 m, the velocities are about 250 m/s. This top layer is interpreted as unsaturated alluvium and unsaturated soil. In the middle layer, whose elevation is between 160 and 193 m, the *P*-wave velocities are about 1800 m/s. This middle layer is interpreted as saturated alluvium. In the bottom layer, whose elevation is between 157 and 160 m, the *P*-wave velocities are about 5000 m/s. This bottom layer is interpreted as the limestone and dolomite bedrock. Because this *P*-wave refraction profile yielded a cross section that is consistent with the geology, the method worked well.

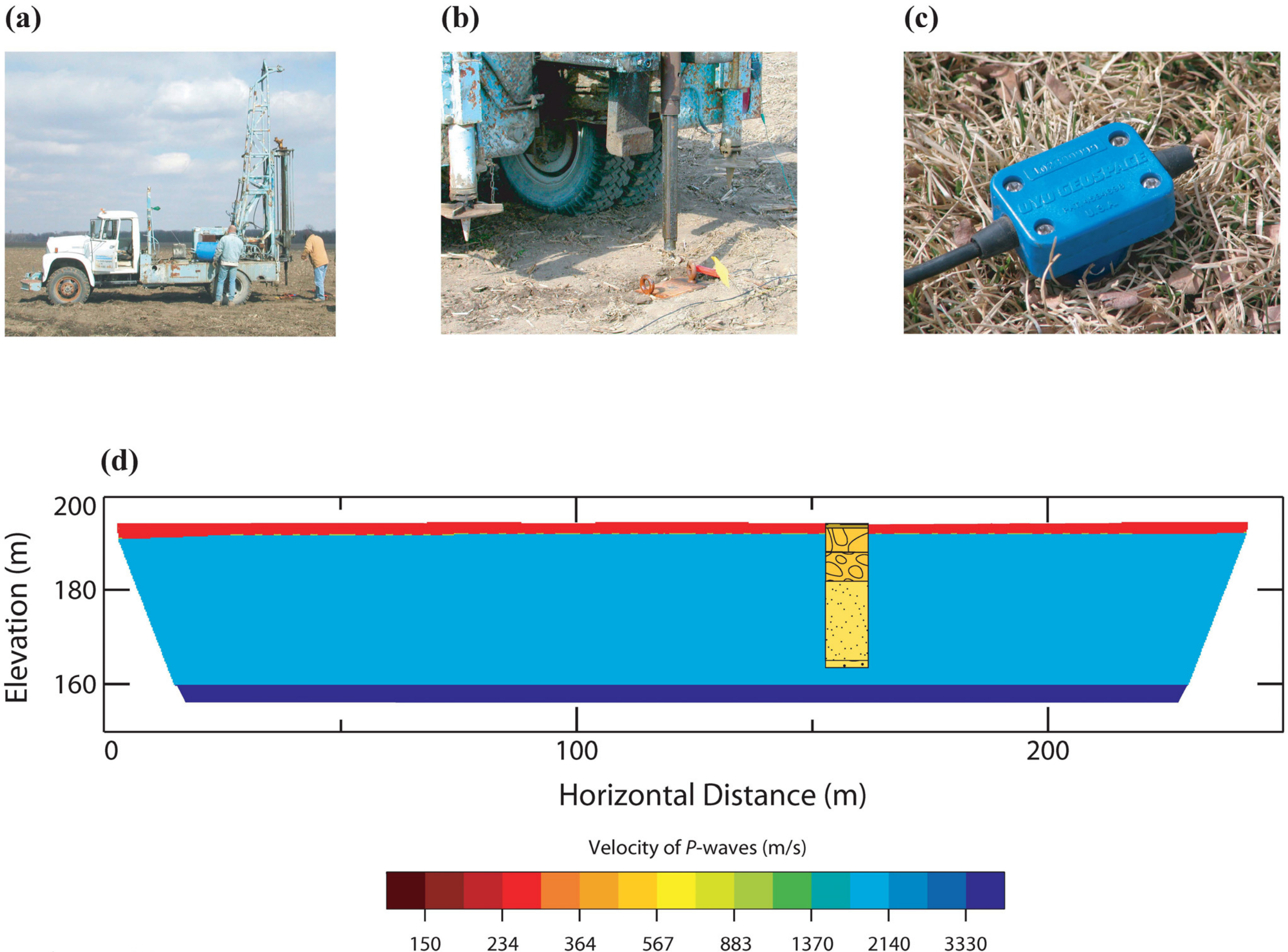

Figure 06
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aggregate deposits

Figure 6. (a) Source that generates *P*-waves for refraction profiling. (b) Close-up view, showing the vertical metal bar and the metal plate. (c) Geophone used to detect *P*-waves. (d) Cross section of *P*-wave velocity. The symbols in the driller's logs are explained in Figure 1c.

CONCLUSIONS AND IMPLICATIONS

The results of the field demonstrations are summarized in table 1, which indicates whether a geologic or hydrologic feature was detected or measured by a geophysical method. Table 1 shows that each geophysical method detected some of the major geologic and hydrologic features associated with the alluvial aggregate deposit, but no method detected all features. The implication is that no geophysical method should be expected to characterize all features of a deposit of alluvial aggregate. Rather, the criterion for selecting a particular geophysical method should be its suitability for characterizing the important features of the deposit. No geophysical method detected the clay layer at the bottom of the alluvium. Nonetheless, a clay layer might be detectable if the stratigraphy were different. For example, if the clay layer were thick and embedded in the middle of the alluvium, then it might be detectable with electrical resistivity profiling or *S*-wave reflection profiling. *S*-wave reflection profiling mapped the interface between layers with different grain sizes, and so this method might be used to map such interfaces in other alluvial deposits.

Table 1. Summary of the field demonstrations, indicting whether a geologic or hydrologic feature was detected or measured by a geophysical method.

Geophysical Method	Geologic or Hydrologic Feature			
	Water Table	Gravel and sand layers within the alluvium	Clay layer at the bottom of alluvium	Thickness of alluvium
Time-domain electromagnetic sounding	No	No	No	Partly[1]
Electrical resistivity profiling	No	Partly[2]	No	Yes
S-wave reflection profiling	No	Yes[3]	No	Yes
S-wave refraction profiling	No	No	No	Yes
P-wave refraction profiling	Yes	No	No	Yes

[1] In the TEM models, the top layer may be interpreted as the alluvium, although its thickness differs considerably from the driller's logs.

[2] When the electrode spacing was 0.5, 1.0, 2.0 and 3.0 m, the electrical resistivity cross sections included anomalies at the ground surface that were interpreted as lenses of sand or gravel.

[3] *S*-wave reflection profiling detected an interface between a layer of fine gravel and sand and another layer of sand.

The importance of these field demonstrations is that the results, which are summarized in Table 1, indicate which geophysical methods might be used to characterize other deposits of alluvial aggregate. For example, if information about stratigraphy is needed, then *S*-wave reflection profiling might be helpful. If information about the topography of the bedrock is needed, then electrical resistivity profiling or the seismic methods might be helpful.

The information in table 1 must be used with caution because the detection of a particular geologic or hydrologic feature depends upon many factors, including the underlying physical principles of the geophysical method. Detection also depends upon the quality and the capabilities of the geophysical equipment used to collect the data and of the software that is used to process and interpret the data. With time, the quality and the capabilities of the equipment and the software will likely improve. Thus, the geophysical methods that are currently incapable of detecting a particular geologic feature might be capable of detecting that feature in the future. Detection depends upon geology, hydrology, and various sources of interference such as electric power lines, roads, and fences. Detection also depends upon the personnel who collect, process, and interpret the data. Accounting for all of these factors requires experience.

Although the time-domain electromagnetic soundings did not work well at this site, the method has worked well in some river valleys in Colorado where the bedrock is shale (Ellefsen and others, 1998). That is, this method can accurately estimate the thickness of an alluvial aggregate deposit if the alluvium has a high electrical resistivity and the layer beneath it has a low resistivity. Thus, this method should be considered when characterizing other deposits of alluvial aggregate.

ACKNOWLEDGEMENTS AND DISCLAIMERS

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Three Decades of Mined Land Reclamation

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ABSTRACT

Since the mid-70s in Colorado and mid-90s in New Mexico, surface mine operators have been required to perform reclamation activities on their industrial mineral properties. These activities are regulated by each state's mining law and associated state agencies, the Colorado Division of Reclamation, Mining and Safety, and the Mining and Minerals Division in New Mexico. While the regulatory details differ, the desired outcome is the same—the return of mined lands to a self-sustaining ecosystem. The challenges of reclaiming severely disturbed lands in the Southern Rocky Mountains are considerable—high elevation, steep slopes, extended drought periods interspersed with extreme storm events, and ambient temperatures ranging from -45°F to +95°F. Many industrial mineral sites offer little topsoil for reclamation use and less irrigation potential.

This paper will identify first-tier concepts critical to returning severely disturbed sites to stable and productive properties at lowest possible cost.

Mined-land reclamation is a science-based art just now coming into its own as an important component of mine planning and cost estimating. Mine operators now understand that it is in their best interest to develop and instrument a comprehensive reclamation plan integrated with their mine plan activities.

The Southern Rocky Mountains are a demanding yet fruitful proving ground for the development of low-cost, effective reclamation techniques.

INTRODUCTION

The reclamation of mined lands in the arid west over the past thirty years has been an evolving process of applied earth sciences to further desired results in a practical and cost effective manner. The intent of this paper is to present one person's field experience in addressing an integral component to successful mined land reclamation activities.

A first step in dealing with severely disturbed lands is attainment of a reasonable degree of mechanical stability on the site (fig. 1). Overall slope and land form stability (highwalls, embankments, waste piles, etc.) can generally be designed and built to conform to standard engineering principles, based on specific site considerations of materials, structure, space, and climate. However, the goal of most reclamation program guidelines is the return of the site to a self-sustaining, productive land use of some preferred type that is stated as such at the onset of reclamation planning and approval prior to mine permit acquisition. A successful vegetative component is usually a critical factor in attainment of ecosystem reconstruction, and mechanical stability (at minimum surface stability) and vegetation become intimately dependent on each in order to support the longevity of both. Without surface stability, attempts to establish vegetation are doomed, and without vegetation, long-term slope stability is dubious. Erosion and sedimentation issues increase over time and eventually lead to potentially larger problems with site control, such as water quality concerns and off-site sedimentation impacts.

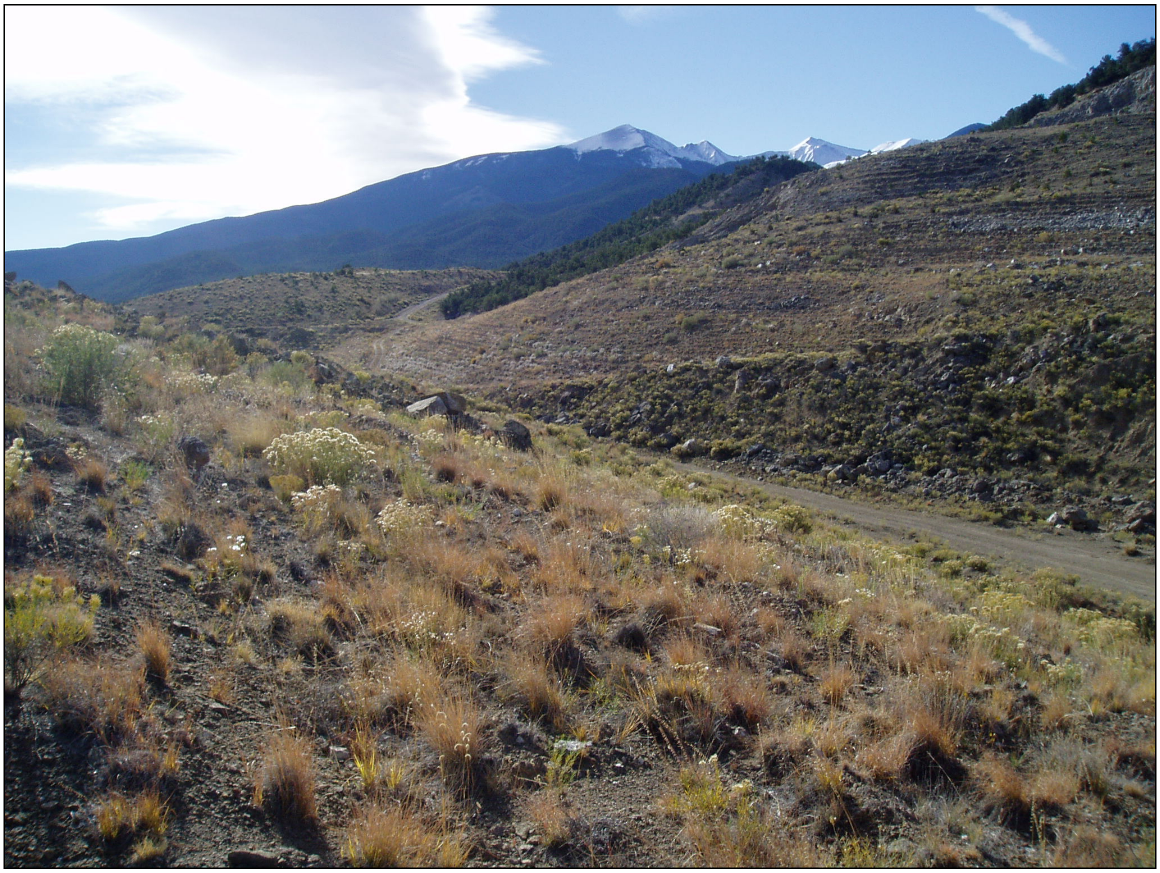

Figure 1. Looking south over reclaimed slopes stabilized utilizing contour furrowing technique—foreground: eight years since treatment; mid-ground, five years; and distance, twenty years.

Moreover, the lack of soils availability on many sites coupled with limited rainfall or irrigation potential leads to problematic vegetative establishment during the first season. At many sites in the arid west, vegetation takes several years to a decade or more to re-establish to a degree of effective mitigation of even minor surface erosion events (fig. 2). Even when topsoil is available, one storm event can remove substantial amounts of material from slopes and wash seed mixtures long distances from their original point of application. Thus, an important first tier approach to land stabilization is the minimization of down-slope transport of planting media and seed, and the maximization of water collection and retention of the seedbed.

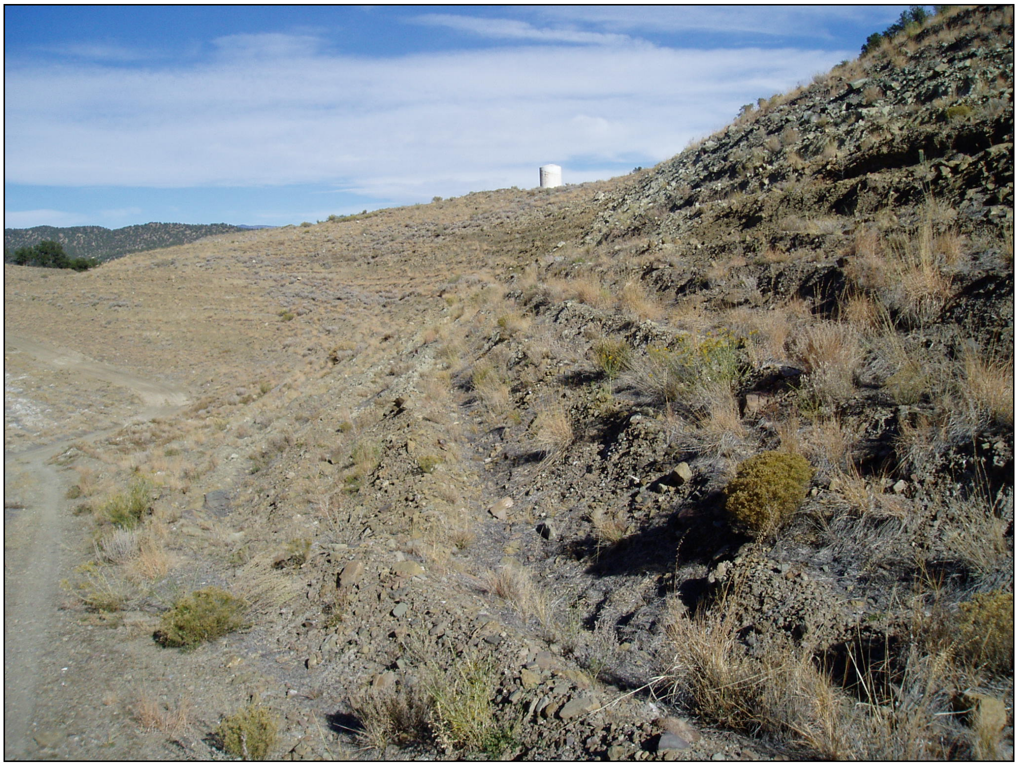

Figure 2. Looking north, steep-slope-reclamation furrowing technique, eight years since installed. Successful erosion control on 1.5:1 slopes.

WHY SURFACE MANIPULATION?

Most state reclamation guidelines subscribe to final slopes of no steeper than 3:1, horizontal:vertical, for finish grades on rock piles and waste dumps whenever possible. In reality, exceptions to this final-slope standard are not uncommon due to placement of dumps prior to rules in effect, lack of space, topographic limitations, permit boundary limitations, and bedrock/highwall interface zones. Even on 3:1 slopes, storm events can incise vertical rills within a short duration, resulting in excessive sediment transport down-slope and removal of precious seed. While standard practices of mulch application and crimping do help to hold the newly disturbed seedbed during storm events, many sites show the beginnings of vertical rilling during the first season after planting. Higher tech (and cost) applications of hydro mulching and/or netting the surface also help to minimize storm event impacts. For the most part, these standard procedures, which work quite well in most sites in the mid-west and east, are commonly subject to failure on many western sites due to medium to high surface water flow velocities attained along slopes during high intensity storm events. Once the flow path is formed along the sloping surface, the channel continues to deepen over time until vertical gully is formed.

By creating a series of breaks in the downslope flow path, surface water flow distances can be limited to a few inches to a few feet before being intercepted by a catchment. The construction of these catchments is simple, low cost, and requires no special equipment not already available on most mine sites. Using conventional equipment such as a bulldozer or excavator, reclamation workers can create structures termed contour furrows, contour ditches, or contour terraces on moderate to steep slopes to result in effective interception of storm derived surface flows. The surface manipulation technique is amenable to a variety of surface materials ranging from fine-grained soils to very rocky substrates. The final result not only intercepts surface run-off due to storm flows, but also retains snow accumulation in the furrows and allows for differential melting of snow while minimizing erosion of the surface during spring run-off. In addition, the furrows accumulate fines and mulch materials, creating a seedbed for first-year and later-year broadcast seeding, and are excellent locations for planting tree and/or shrub seedlings. Contour furrows are dynamic structures, subject to a slow but steady softening and rounding over several seasons, allowing for vegetation establishment over a number of years while limiting uncontrolled rates of erosion and subsequent gully formation (fig. 3 and 4).

Figure 3. Looking east on slopes twenty-seven years since grading. Contour furrows barely discernable.

Figure 4. After twenty years of "controlled" erosion of contour furrows, vegetation has had time to establish large seed producing species such as *Atriplex Canscenes*, Fourwing Saltbush.

DESCRIPTION OF APPLICATION OF FURROWING TECHNIQUE

A bulldozer is the most common machine used for contour furrow installation, although an excavator can be employed to result in a similar result. In general, less steep slopes and finer grained materials are best worked with a smaller machine, while a larger dozer best handles the steeper slopes and rockier terrain. Machines ranging in size from D-4 to D-9 have produced excellent results (fig. 5).

This technique can be applied after final grading of a slope and after topsoil, if available, or planting media is in place at the surface (fig. 6). The machine operator usually utilizes an eye level or has engineering reference points in place of equal elevation at the top of the slope to be worked. The machine work begins at the top of the slope with a cut along the contour. The blade cut creates a windrow of soil/fines deposited on either side of the blade as it moves across the slope. The machine is level at all times and angled slightly (1°–2°) into the slope of the area being worked. The machine work proceeds along the contour until it reaches the periphery of the area being worked, at which time the machine is turned around and continues back on its original transect, slightly below (1 ft–1. 5 ft) below the original cut. This second cut nearly removes the first dozer trail cut along the contour line, with only the upslope windrow remaining on the slope. Successive cuts below cuts one and two are repeated until the entire slope from top to bottom is left with a rough terraced or ditch like appearance from top to bottom. Rocks encountered during contour furrowing will eventually be pushed to one of the windrows. Bedrock encountered can be ripped to facilitate continuous windrow formation, or loose material can be feathered up to the bedrock outcrop contact. In areas of steep slopes where bedrock outcrops at various locations along the slope, the feathering of loose soil and rock up to the bedrock outcrop will minimize gully formation along the bedrock/soil contact while creating a more natural final slope configuration. Trails can be left at intervals along the slope to facilitate access for mulching equipment or personnel, or the entire slope can be contour furrowed from top to bottom. The rough surface left by this work is now ready for seeding and mulching.

Figure 5. Looking south over steep erosion controlled slopes(left foreground) and backfilled former mine benches(right foreground).

Figure 6. Native plants established in extremely rocky sites. No topsoil was available at this site.

In applications where a capping of soil is used to cover underlying materials, a sufficient depth of capping material should be placed so that the underlying material is not exposed during furrow construction. A smaller dozer can be used in these cases with less depth to each dozer cut and smaller frequency of furrow placement (0.75 ft–1 ft) between each furrow and the furrow above and below. When the furrows are constructed with small frequency between each cut, the windrows are stacked against one another as they progress from top to bottom of the slope. The capping material is re-arranged more than removed from the slope by furrow construction, although care must be taken not to excavate deep enough to expose unwanted substrate materials.

As mentioned earlier in this paper, the contour furrows are dynamic structures subject to erosion over several years of weathering. During the first few seasons, vegetative growth will be more pronounced in the ditches compared to the outslope of each individual furrow. As time goes on, grasses and shrubs will move onto the outslope of the furrow and the furrow will “soften” with erosion until the furrow’s impact as a horizontal line along the slope will disappear (fig. 7). Slopes manipulated in this manner ten years ago now show little to no contour furrow, but have remained stable and free of surface rilling or gullying while vegetation cover has slowly increased (fig. 8). In very rocky applications or in cases where the furrows were placed at higher frequencies, the process can be accelerated using livestock. Large round bales of hay can be rolled from the top of the slopes, inducing cows to move along the seeded and mulched furrows. The cows trample mulch, manure, and the rough ground and speed up the process of normal weathering of the furrows.

Figure 7. Twenty years since final grading, this site has little to no contour furrow visible, good grass, shrub, and tree establishment. No topsoil was available.

Figure 8. Tree damage due to deer browse. Twenty years since seedling installation.

CONCLUSIONS

Contour furrowing is a simple, low-cost surface manipulation technique that can have distinct advantages in attaining mined land reclamation success in arid sites. This work can be accomplished with standard mining equipment for a few hundred dollars per acre and can be used on moderate to very steep slopes. Contour furrowing has proven to be effective in eliminating unwanted surface erosion and gully formation for up to two decades and longer while vegetation has established (fig. 9 and 10). Furrowing promotes water collection and retention on slopes where soils are otherwise subject to storm erosion or planting media is marginal in quantity and/or quality (fig 11. and 12). This simple technique has great utility in efforts to reclaim severely disturbed lands with a minimum of cost.

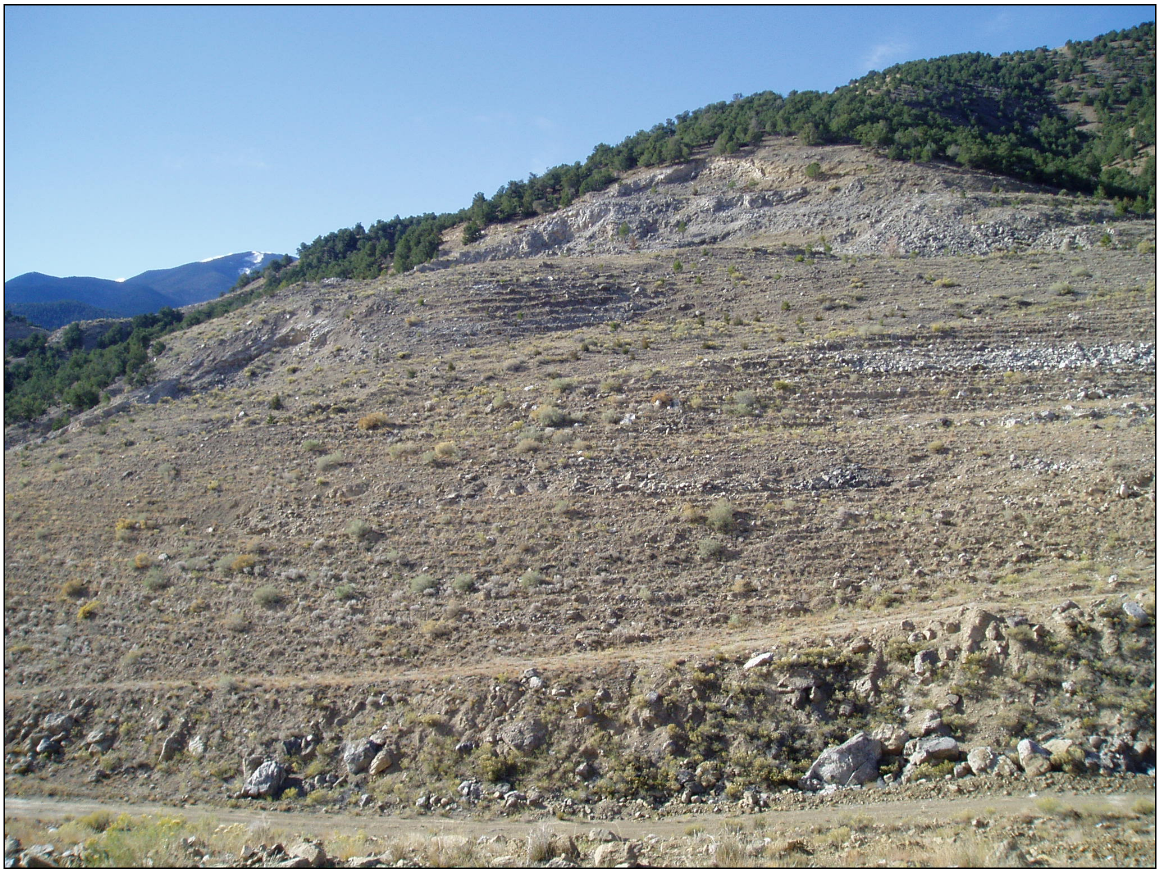

Figure 9. Top third of photo—reclamation work after twenty five years; bottom two-thirds, slopes after five years.

Figure 10. Looking north-northwest from matured reclamation areas in foreground to progressively newer reclamation areas in distance.

Figure 11. Looking west at five-year-old contour furrows constructed through bedrock outcrop zone of slope. April photo only shows shrub development.

Figure 12. Contour furrows hold snow, releases melt-off slowly into ditches.

Volumetric Analysis & Three-Dimensional Visualization of Industrial Mineral Deposits

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ABSTRACT

Base and precious metal deposits are typically characterized by a single parameter such as the total weight of mineable gold. Industrial mineral deposits, on the other hand, are characterized by their end-use. For example, the volumetric evaluation of a limestone deposit depends upon who's buying the product. The concrete industry has a suite of evaluation parameters such as silica content and abrasion coefficients. Conversely, pharmaceutical-grade limestone buyers are more focused on the calcium/magnesium ratio and various impurities. As a consequence, many industrial mineral deposits must be re-evaluated as the nature of the market demand changes. Different customers mean different specifications. Quarry configurations are therefore indirectly determined by the end-product requirements set forth by the customer. This is the ugly reality of industrial mineral mining that is unappreciated by our base/precious-metal colleagues.

Computerized deposit modeling provides a means for tailoring a mine plan based on the end-use specifications. The basic strategy involves the creation of a borehole database that includes analytical results for various physical and chemical properties as a function of depth. Once the database has been created, visualizations such as cross-sections, fence diagrams, and block diagrams may be quickly generated to check the validity and geological reasonability of the modeling. The next step involves the calculation of volumetrics and optimal pit-designs based on a series of user-defined parameters.

The foundation of these analyses involve the creation of imaginary block models in which a site is subdivided into a series of three-dimensional cells called "voxels" (a medical term for volumetric elements). Values are estimated for these voxels based on their proximity relative to downhole data. For example, a clay deposit may involve the creation of separate models representing shrinkage, brightness, and slip. These models are then filtered and combined into a final model that shows where all of the parameters (models) meet a set of user-defined criteria. The net result is high-grade, or "surgical" mining in which the quarry is designed to maximize profitability rather than simply mining the entire lease and relying on the sorting/milling process to separate the ore and the non-ore.

A healthy level of skepticism must be employed when using computer software to compute resource volumetrics. The algorithms or methods used to create the volumetric models have limitations that may be acceptable for one type of deposit while being completely inappropriate for another. For example, a sand and gravel deposit requires an approach that is completely different than the methods used to evaluate a phosphate reserve. The best way to avoid misuse is to always compare "slices" through the models with borehole logs that show the original data. These cross-sections are used to make sure that the model "honors" the data. Just as importantly, cross-sections should be evaluated to make sure that the modeling conforms to the expected geology.

The era of guesstimates has been terminated by the Sarbanes-Oxley Act of 2002. Computerized modeling of industrial mineral reserves provides an inexpensive tool for accurately and quickly estimating volumetrics within a changing marketplace.

INTRODUCTION

Computerized evaluations of industrial mineral deposits have been in use since the late 1950s. Since that time, the public-domain and commercial software has become more sophisticated and easier (in a relative sense) to use. This paper describes the methods that are used by these programs. It is important to note that these descriptions are not intended to be performed manually. Instead, the intent is to demystify the "black box" and create an understanding of the advantages and limitations of automated resource computations.

The modeling and economic evaluation of industrial mineral deposits can range from simple to complex. A simple example might involve the evaluation of a clay deposit for geomembranes at a landfill. Conversely, a complex example would involve the evaluation of the same deposit for use as a rubber additive. These complexities exist on two levels; geological and economic.

Geological Complexities

Industrial mineral deposits can be so geologically complicated that ore-body geometries can only be understood after they have been mined. For example, consider a sand and gravel operation within a braided Pleistocene glacial outwash plain (fig. 1). Creating a three-dimensional model of the environment of deposition (*i.e.* drainage meanders, point bars, cross-stratification, lag deposits, etc.) would isolate optimal zones for sand and/or gravel extraction, minimize waste, and therefore optimize profits. Practical realities, on the other hand, preclude such an analysis and the process of sorting the good material from the bad typically falls upon the processing facility, a screen plant in this case.

Figure 1. Glacial outwash. (Source: U.S. Geological Survey)

Economic Complexities

Metal deposits are typified by a single number (total reserves) for a given commodity. For example, a gold deposit may be described in terms of the total grams of economically extractable gold. Conversely, the economic resources within many types of industrial mineral deposits depend upon the end-user requirements. Consider the differences between the evaluation of a limestone deposit for pharmaceuticals versus riprap for river channelization. As a consequence, industrial mineral deposits must be re-evaluated based on completely different criteria as markets and end-user requirements change. Gold is gold but limestone depends on who you're planning on selling it to.

DATA MANAGEMENT

The raw data that is used for industrial mineral deposit modeling can be classified into two major types: borehole and non-borehole data (fig. 2). The management of borehole data is very different than non-borehole data. Specifically, borehole data requires a relational database management system (*e.g.* Access, FileMaker, SQL, Oracle, etc.) whereas non-borehole data (with the exception of land ownership) can be handled with simple "flat" file managers (*e.g.* Excel or Lotus).

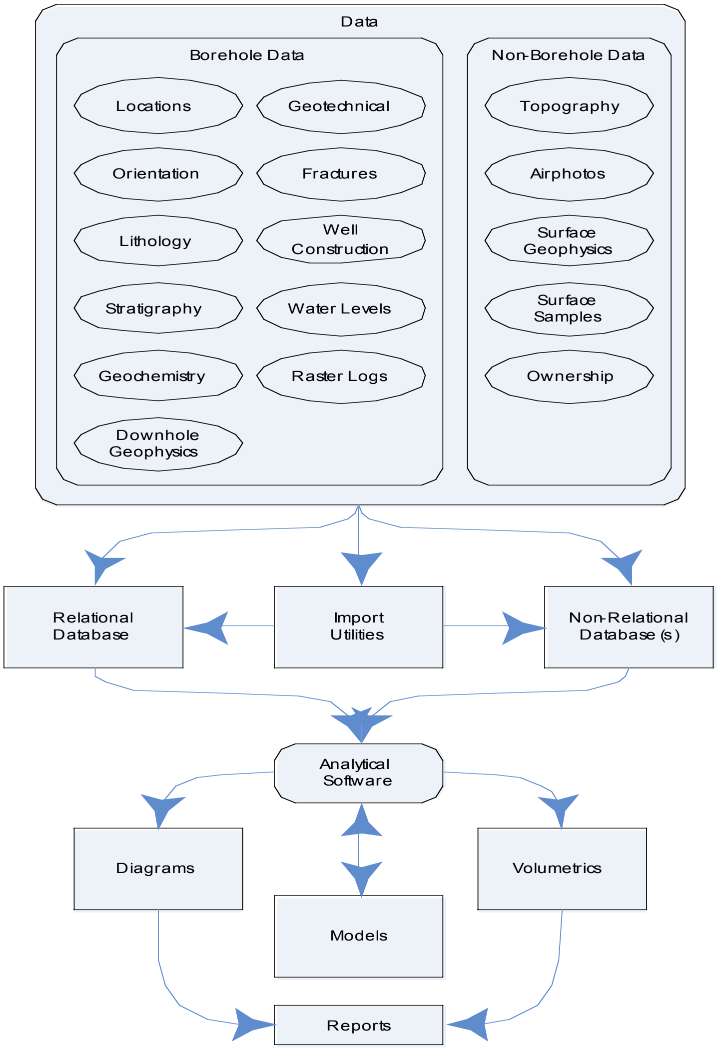


Figure 2. Process flowchart depicting transformation of data into reports.

Non-Borehole Data

Non-borehole data includes airphotos, land ownership, surface geochemistry, surface geophysics, and topography. These datasets are typically stored in separate files (table 1). Organizing these disparate data sets into a single database with downhole data is a somewhat Sisyphean task. Instead, most software will read these files in their native format.

Table 1. Non-Borehole Data Types.

Data Type	File Format
Airphotos:	GeoTIFF (Tagged Image File Format) with embedded geographic information. JPEG (Joint Photographic Experts Group) PNG (Portable Network Graphics) TIFF (Tagged Image File Format)
Land Ownership:	DBF (IBM DataBase File) and SHP (ESRI Shape File)
Topography:	DEM (Digital Elevation Model) DXF (AutoCAD data eXchange Format)
Surface Geochemistry:	ASCII (American Standard Code for Information Interchange) XLS (Microsoft Excel)
Surface Geophysics:	Many vendor-specific formats.

Borehole Data

Borehole data (table 2) may include lithology, stratigraphy, geochemistry, downhole geophysics, geotechnical properties, and water levels. Borehole data cannot be stored in simple “flat” files (*e.g*. Excel spreadsheets) due to the relational nature of the data. Instead, downhole data must be stored within a relational database in which data-specific tables are linked to a master list of boreholes. The reason for this structure is based on the fact that downhole data is highly variable. For example, one borehole may contain compaction analyses that are sampled on 5-meter intervals while another borehole is sampled at 1-meter intervals. Storing this type of information in a spreadsheet is impractical.

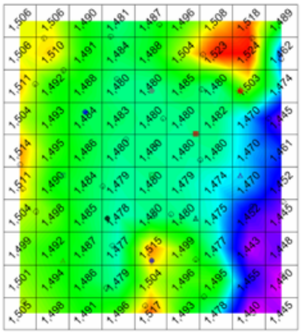
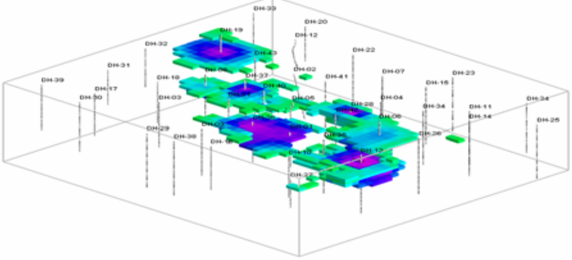
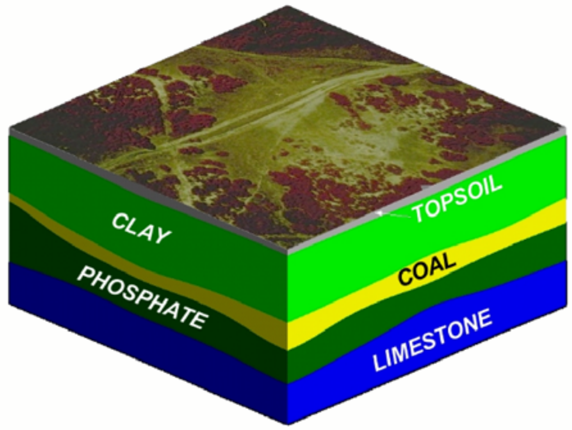
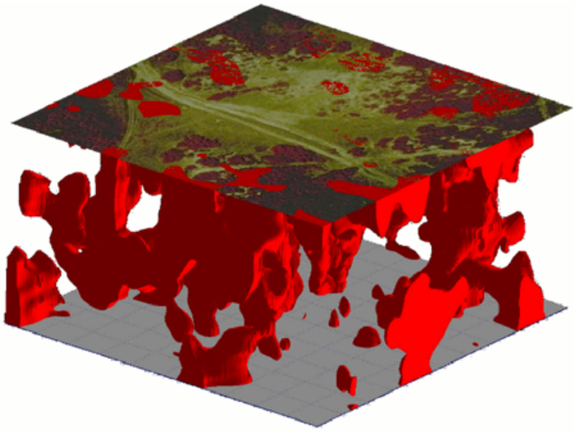
Table 2. Borehole Data Types.

Data Type	Description / Examples
Location Information	Borehole ID, X and Y location coordinates (Eastings and Northings), surface elevation, total depth, map symbol, comments, range, township, section, legal description, longitude, latitude, etc
Orientation	Downhole survey information (depths, bearings, and inclination).
Lithology	Observed downhole lithologies (as opposed to interpreted stratigraphy).
Stratigraphy	Interpreted downhole stratigraphic data.
Quantitative Interval-Based Data	Downhole data that was sampled over one or more depth intervals, such as geochemical or geotechnical measurements.
Quantitative Point-Based Data	Downhole data that was sampled at individual points, such as geophysical or geotechnical measurements
Fractures	Sub-surface fractures information (dip direction, dip amount, aperature, etc.)
Water Levels	Dates and water levels for the borehole.
Raster Images	Raster images (*e.g*. core, photomicrographs, cuttings, etc.)
Borehole Construction	Construction materials at particular depths and diameters.

MODELING

“Modeling” refers to the process of creating a spatial array of estimations. The parameter that is being estimated may be the thickness of the ore, the grade of the ore, or some other property that is useful for the evaluation of the resource. These arrays may be two or three-dimensional depending upon the number of independent variables. In a two-dimensional array (also referred to as a "grid model"), the dependent variable (z) is a function of the horizontal (x,y) coordinates. In a three-dimensional array (also referred to as a solid or block model), the dependent variable (g) is a function of the horizontal (x,y) and vertical coordinates (z). Grids are used to model topography, stratigraphic contacts, isopachs, and water levels, while solids are used to model geochemistry, ore grades, and geotechnical properties (table 3).

Table 3. Primary types of geological models.

Grid Models	Block Models
	
Stratiform (Based on Grid Models)	Non-Stratiform (Based on Block Models)
	
Examples: Coal, Clay, Groundwater, Gypsum, Hydrocarbons, & Phosphates	Examples: Compaction, Contaminants, Geothermal, Metal, Sand & Gravel

The key difference between grid models and block models is that a gridded surface (*e.g.* a stratigraphic contact) cannot fold or wrap under itself whereas an isosurface within a block model can. Stated differently, when dealing with grids, there can only be one z-value for any given xy coordinate. On the other hand, when dealing with block models, there can only be one g-value for any given xyz coordinate. Another major difference is that gridding is computationally fast while block modeling can be very slow. In fact, block modeling was the impetus for the creation of supercomputers (*i.e.* building atmospheric models for nuclear weapons fallout dispersion during the cold war).

In practice, numerical models of most industrial mineral deposits employ a combination of gridding and block-modeling. For example, a deposit may have a discrete top and bottom but the grade may vary vertically between these two surfaces (fig. 3).

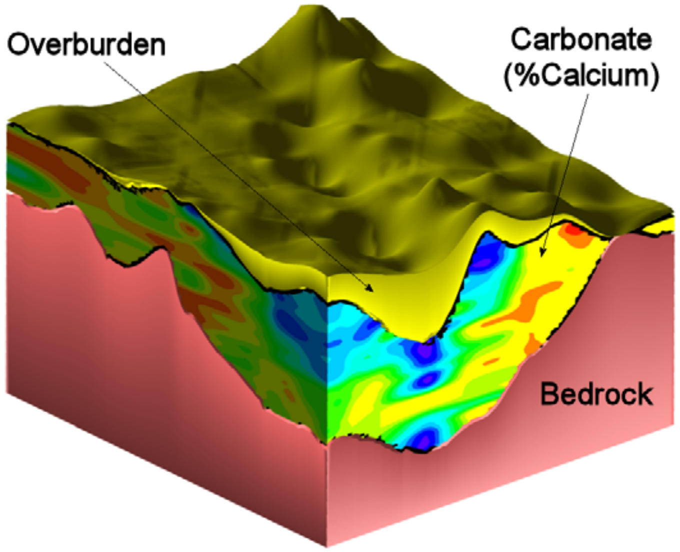


Figure 3. "Hybrid" model in which the surface topography, overburden base, and carbonate base are modeled via grids while the calcium content within the carbonate is based on a block model.

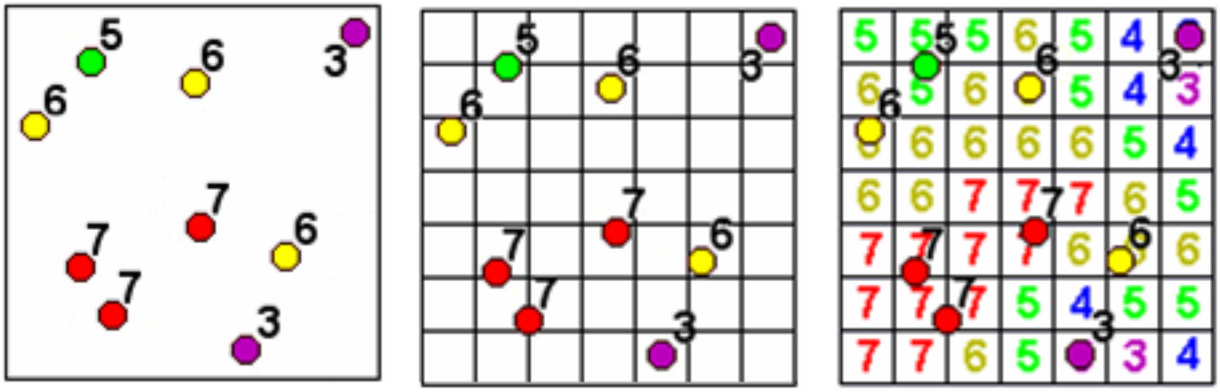
Two-Dimensional Modeling (Gridding)

Consider the evaluation of a clay deposit in which the only important parameter is the thickness of the clay (*i.e*. the clay grade is homogeneous or "isotropic"). Variations in the clay thickness encountered within nine boreholes are depicted within Figure 4a.

The first step in the modeling process is to superimpose an imaginary grid (fig. 4b) over the project area. This grid defines the resolution of the subsequent model in a manner analogous to pixels (picture elements) within a digital image. Specifically, as the pixels become smaller, smaller features are resolved at the expense of computer memory and speed. A general guideline for dimensioning the grid is to set the cell dimensions equal to the average minimum distance between the control points (*e.g*. boreholes).

Once a grid has been established, the clay thicknesses at the center of each grid node are estimated. These estimations are based on a weighted average of the values associated with the surrounding control points (fig. 4c). A variety of interpolation methods or "algorithms" are available for performing these estimations. A popular and simple technique called "inverse distance weighting" (IDW) varies the influence of surrounding points based on the inverse of the distance between the control point and the interpolated point. Another technique, called "kriging" varies the influence of surrounding points based on a statistical analysis of their relative distance and direction.

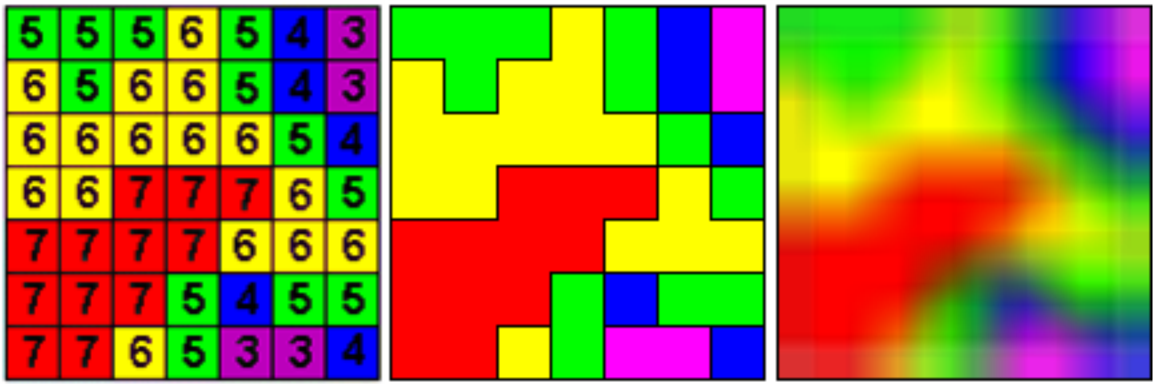
Grid models are commonly used to produce color-coded contour maps by averaging the regions between cells (fig. 4d). In fact, most computer contouring uses gridding as a preliminary, behind-the-scenes, step towards producing contours. There are, however, many more things that can be done with grids, including volumetrics.



A. Map depicting clay thicknesses encountered within nine boreholes.

B. Map depicting imaginary grid superimposed over project area.

C. Color-coded clay thickness estimations.



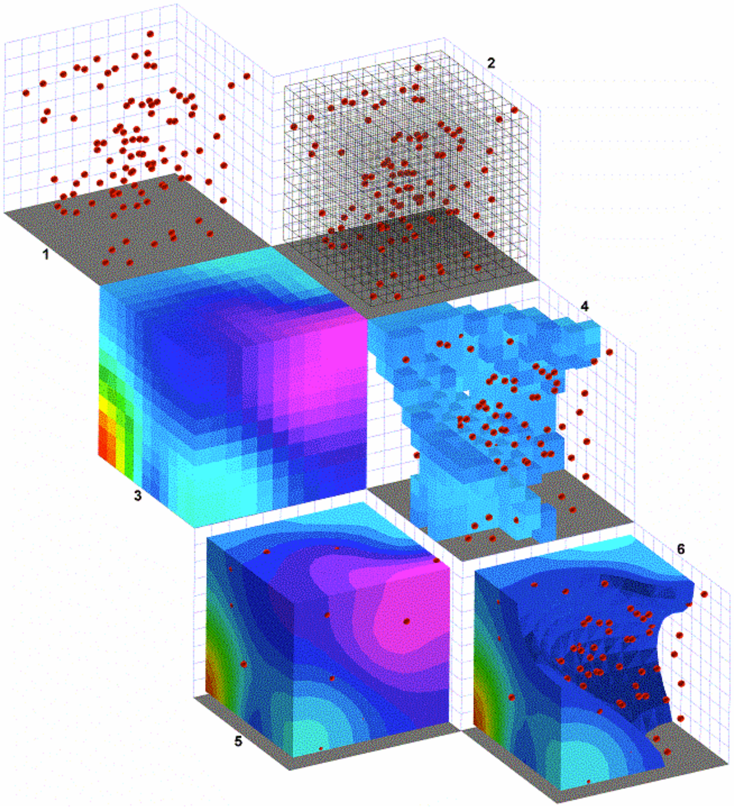
5	5	5	6	5	4	3
6	5	6	6	5	4	3
6	6	6	6	6	5	4
6	6	7	7	7	6	5
7	7	7	7	6	6	6
7	7	7	5	4	5	5
7	7	6	5	3	3	4

D. Converting a numerical grid model into a color-coded contour map.

Figure 4. Gridding & Contouring Process.

Three-Dimensional Block Modeling

Block modeling (fig. 5) is simply the three-dimensional version of gridding. The original data points typically consist of quantitative downhole data (*e.g.* geochemistry, ore grades, physical properties, etc.).



(1) Starting with irregularly distributed control points (*i.e.* downhole data) …

(2) An imaginary three-dimensional lattice (matrix of blocks) is constructed. Grade estimates are then computed for each voxel within the model based on a distance/value weighting method.

(3) Color-coding the voxels (volumetric elements) based on the estimated grades produces a block diagram.

(4) Showing only the voxels within a specified range produces a diagram that depicts the shape of the ore body

(5) Isosurfaces are essentially three-dimensional contours. Unlike voxels (3 & 4 above), they are implicitly smoothed.

(6) An isosurface cutoff is used to show a smoothed outline of the ore body.

Figure 5. Block modeling.

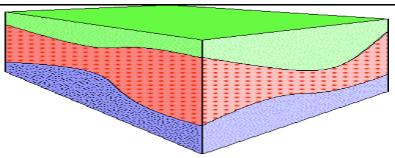
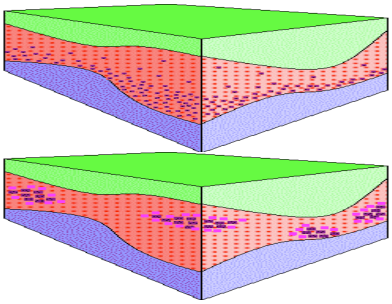
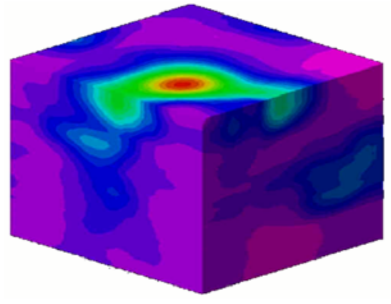
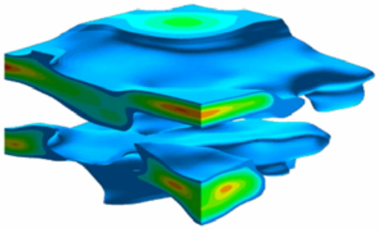
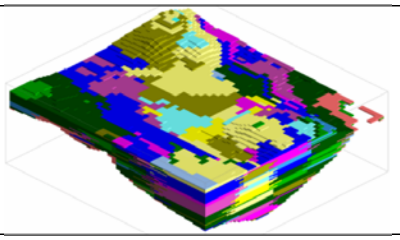
Modeling Strategies

Selecting the proper modeling technique (gridding or block modeling) as well as the algorithm (*e.g.* inverse distance weighting, triangulation, polynomial trend, kriging, etc.) represents the biggest hurdle for the novice user.

Many types of industrial mineral deposits, such as clay, consist of “layercake” geology in which an economic resource is sandwiched between two non-economic layers. If the grade of the material does not vary, laterally or vertically, the deposit can be effectively modeled by gridding the top and bottom of the ore layer. Conversely, if the grade varies laterally and/or vertically, then a block modeling method, constrained by upper and lower grids (the top and base of the unit) should be used. General guidelines are graphically summarized within Table 4.

Table 4. Modeling strategies.

Type of Deposit	**Diagram**	**Description**	**Modeling Method**
Stratiform – Isotropic		Layered deposit in which grade does not vary laterally or vertically.	Gridding

			
Stratiform – Anisotropic		Layered deposit in which grade varies laterally and/or vertically.	Block Modeling Constrained By Gridding
Non-Stratiform – Isotropic		Non-layered deposit in which grade does not vary laterally or vertically.	Block Modeling
Non-Stratiform – Horizontally Anisotropic		Non-layered deposit in which grade is more consistent (varies less) horizontally than vertically.	Block Modeling with Horizontal Biasing
Stratiform – Discontinuous – Non-Gradational		Layered deposit with discrete, discontinuous layers.	Lithoblending (Special algorithm designed exclusively for lithology.)

Multivariate Modeling

The economics of industrial mineral deposits are often determined by more than one property (table 5). These properties are often dictated by the end-user specifications. Additionally, a given deposit may be quarried for more than one end-user, each with their own set of material requirements. It is therefore necessary that deposits be modeled for multiple attributes.

Table 5. Sample variables associated with different types of industrial mineral evaluations.

Commodity	Pertinent Parameters (Specifications)
Aggregates	Aggregate Abrasion Value (AAV), Aggregate Crushing Value (ACV), Ten Percent Fines Value (TFV), Aggregate Impact Value (AIV), Polished Stone Value (PSV) Artificial Aggregates (Hardness), Magnesium Sulphate Soundness Value (MSSV), Aggregate Size, Aggregate Grading, Flakiness, Grading Zone, Moisture Content, Water Absorption, & Frost Susceptibility
Agricultural Limestone	Dry Weight Analysis, Percent Calcium, Percent Magnesium, Percent Magnesium Oxide, Percent Calcium Oxide, Calcium Carbonate Equivalent (CCE), Effective Neutralizing Value (ENV), Screen Test Results,
Filler-Grade Clay	Cone, Fired Color, Fired Shrinkage, Water Absorption, Reflectance, Brightness, Specific Gravity, Mohs Hardness, Moisture Content, Chemical Content, Particle Size Distribution

The basic idea behind multivariate spatial analysis is analogous to Venn diagrams or overlaying transparent sheets with outlined regions of interest and looking for areas of commonality. This is the “analog approach” that is illustrated within Figure 6, a hypothetical agricultural limestone study.

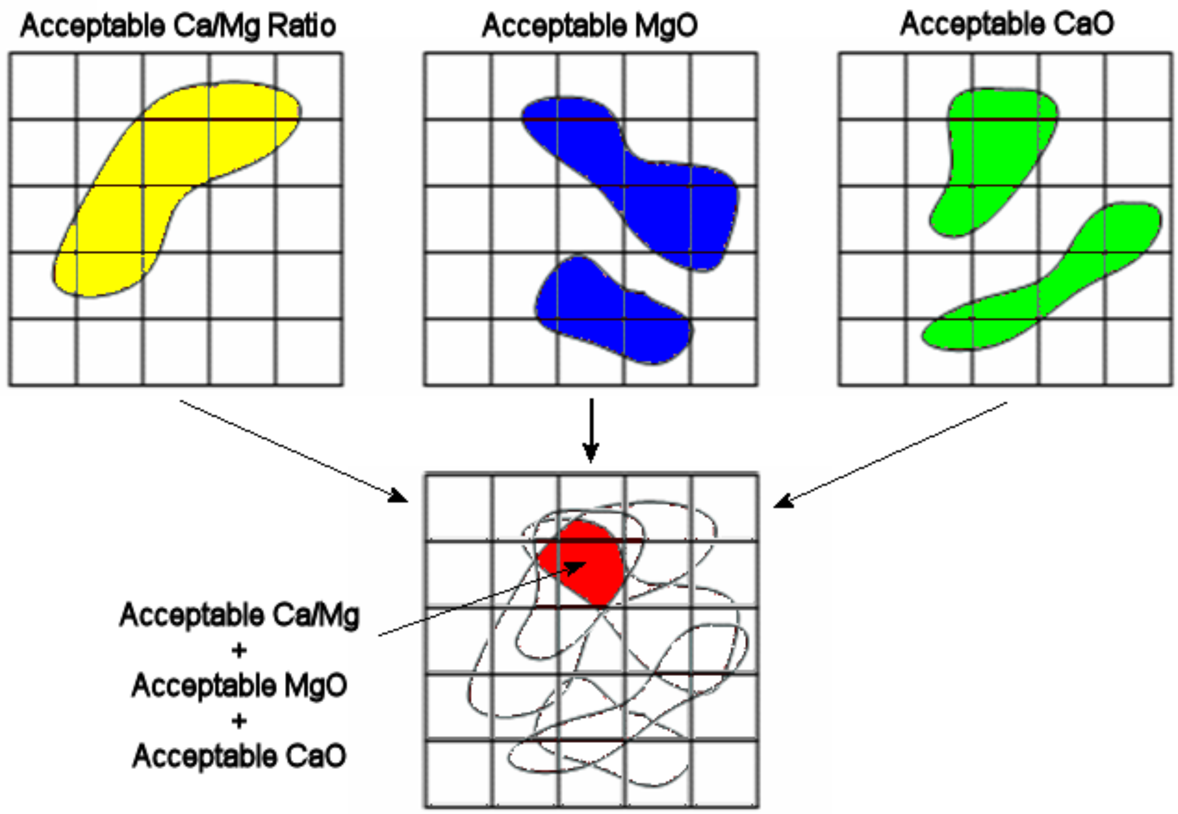
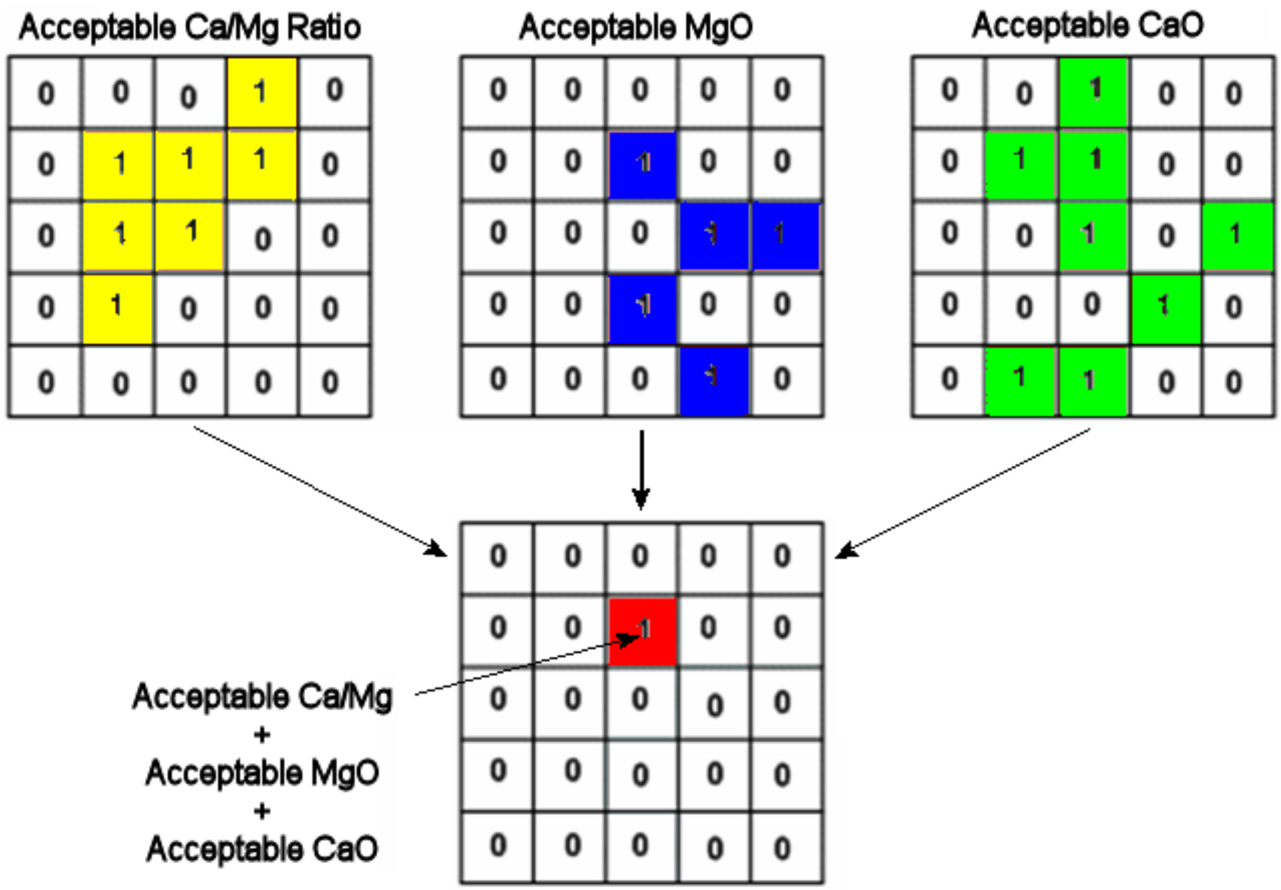


Figure 6. Agricultural limestone characteristic maps overlain to determine optimum area for mining.

The digital approach to the previous example (fig. 7) albeit cumbersome to humans if attempted manually, is the foundation of computer-based spatial analysis. This method converts the maps to grids in which the acceptable regions are represented by ones and the unacceptable regions by zeroes. The grids are then multiplied, on a cell-by-cell basis to produce the final map showing where all three models are in agreement. Compare this methodology with the analog approach depicted within Figure 6.



Acceptable Ca/Mg Ratio

0	0	0	1	0
0	1	1	1	0
0	1	1	0	0
0	1	0	0	0
0	0	0	0	0

Acceptable MgO

0	0	0	0	0
0	0	1	0	0
0	0	0	1	1
0	0	1	0	0
0	0	0	1	0

Acceptable CaO

0	0	1	0	0
0	1	1	0	0
0	0	1	0	1
0	0	0	1	0
0	1	1	0	0

Acceptable Ca/Mg
+
Acceptable MgO
+
Acceptable CaO

0	0	0	0	0
0	0	1	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0

Figure 7. Agricultural limestone characteristic models multiplied together to determine optimum area for mining.

This approach to resource evaluation is relatively simple to visualize in two-dimensions as shown by the preceding examples. It is also arguably inferior to the analog method. When used in three dimensions, however, it is vastly superior to analog methods. Imagine trying to perform a Venn analysis by hand with complex three-dimensional shapes. By comparison, a computer program can perform a Boolean operation with two large block models in a matter of seconds. The irony of the digital approach is that the math and logic are exceedingly simple (*i.e.* determining if one number is greater than another and multiplying zeroes and ones) but the nomenclature is intimidating to the uninitiated.

Sand & Gravel Case Study

In the following case study involving multivariate modeling, a series of exploration boreholes were drilled. Samples were taken every five feet and sieved in order to determine the relative percentages of sand, gravel and clay (or other non-sand/gravel material). These samples were restricted to the interval below the base of the soil profile and the top of the bedrock.

Step 1. The borehole locations, stratigraphy (table 6), and sieve analyses (table 7) were entered into a relational database.

Table 6. Information that was recorded for each borehole.

Name	Unique borehole identifier (*e.g*. BH-01, BH-02, etc.)
Easting	UTM easting from GPS (in feet)
Northing	UTM northing from GPS (in feet)
Elevation	Elevation from GPS (in feet)
Soil Depth	Depth to base of soil (in feet).
Bedrock Depth	Depth to top of bedrock (in feet).
Total Depth	Total depth of borehole (in feet).

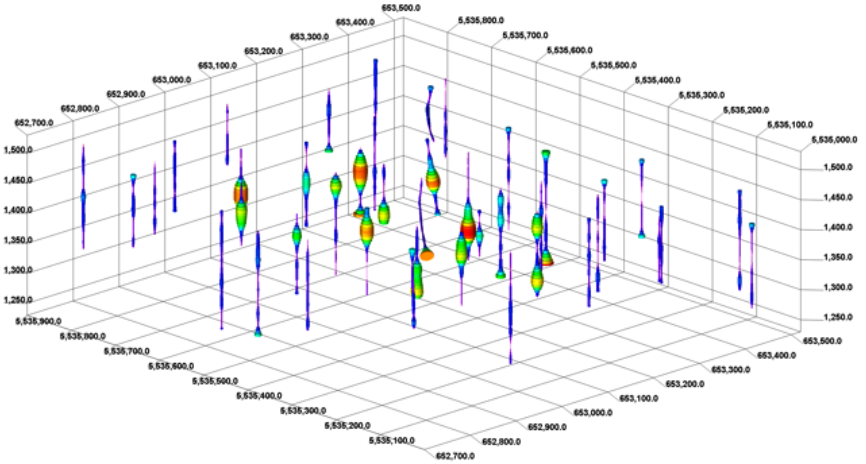
Table 7. Information that was recorded for each sample interval.

Depth-1	Depth to top of sampled interval (feet).
Depth-2	Depth to base of sampled interval (feet).
Sand	% Sand (0 to 100)
Gravel	% Gravel (0 to 100)
Clay	% Clay or other non-sand/gravel material(0 - 100)

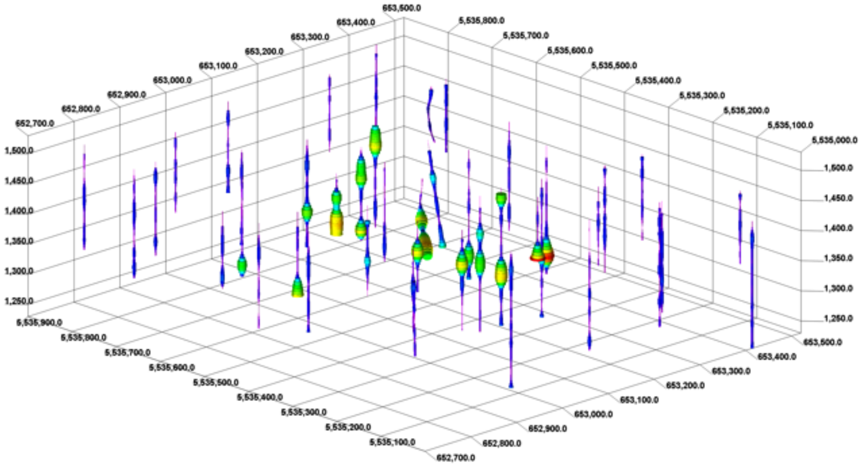
Data entry is the most laborious and error-prone step within the entire process or automating resource evaluations. For this reason, it is imperative that diagrams of the "raw" data (see Step 2) be created before attempting the modeling in order to check for errors in the data such as mistyped borehole coordinates, spurious data values, and transposed coordinates. It is also useful to perform simple statistical analyses, such as data histograms to check for unreasonable outliers.

Step 2. Separate three-dimensional percentage log diagrams (table 8) were created to show the relative concentrations of each constituent (% sand, % gravel, and % clay). The percentages are depicted as color-coded cylinders in which the cylinder radius is proportional to the component concentration while the colors are scaled in a similar fashion from the "cold" colors (purple) through the "hot" colors (red).

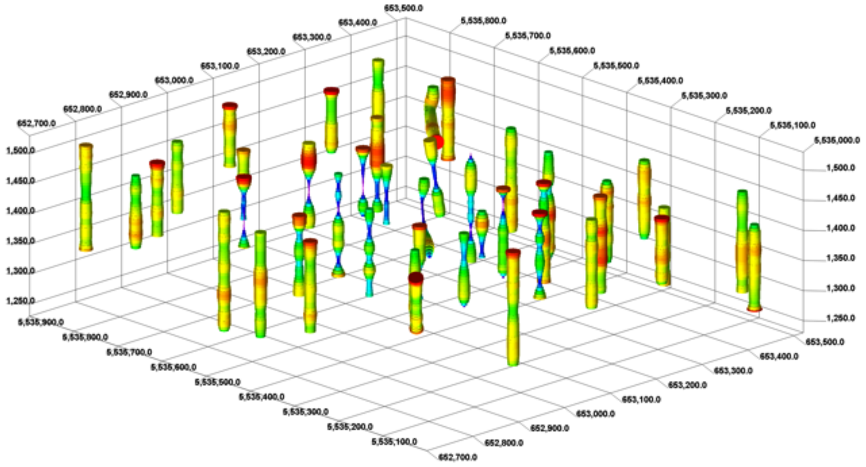
Table 8. 3-Dimensional Log Diagrams.



% Sand



% Gravel

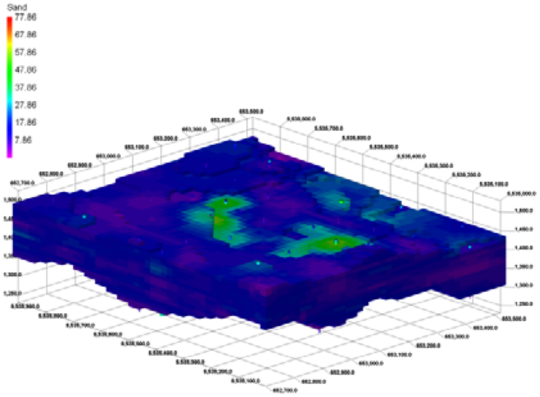


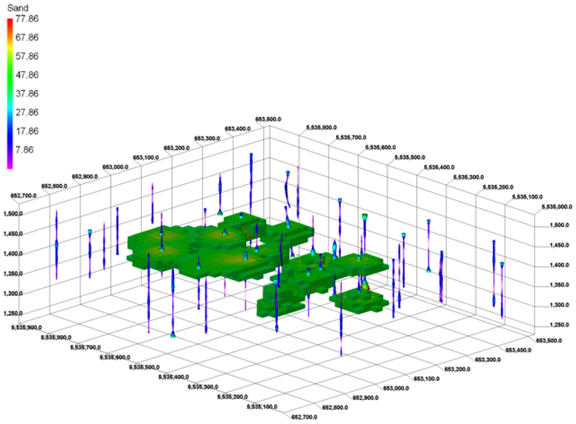
%Clay

Step 3. Solid "block" models for the sand, gravel, and clay data were created by using a block modeling algorithm and truncated by grid models representing the base of the soil overburden and bedrock (material below the sand/gravel unit). Each of these models was then filtered based on acceptability cutoff levels (table 9).

Table 9. Initial sand, gravel, and clay models and filtered models showing acceptable levels of sand, gravel, and clay.

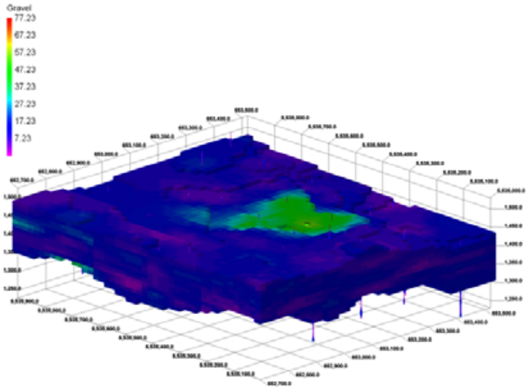
% Sand

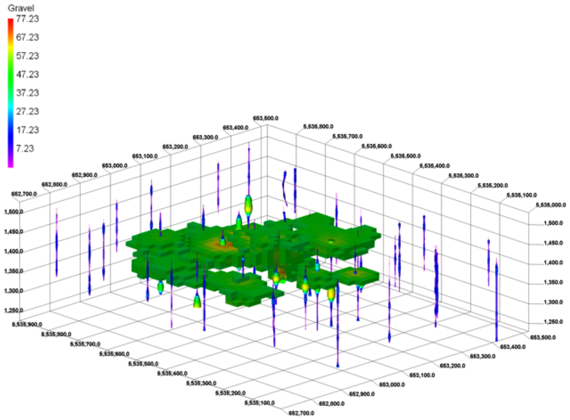




Sand > 40%

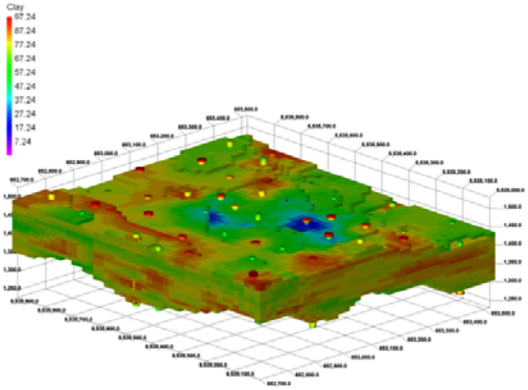
% Gravel

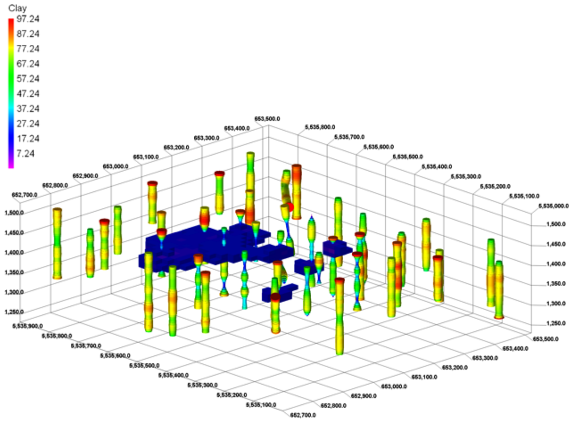




Gravel > 40%

%Clay



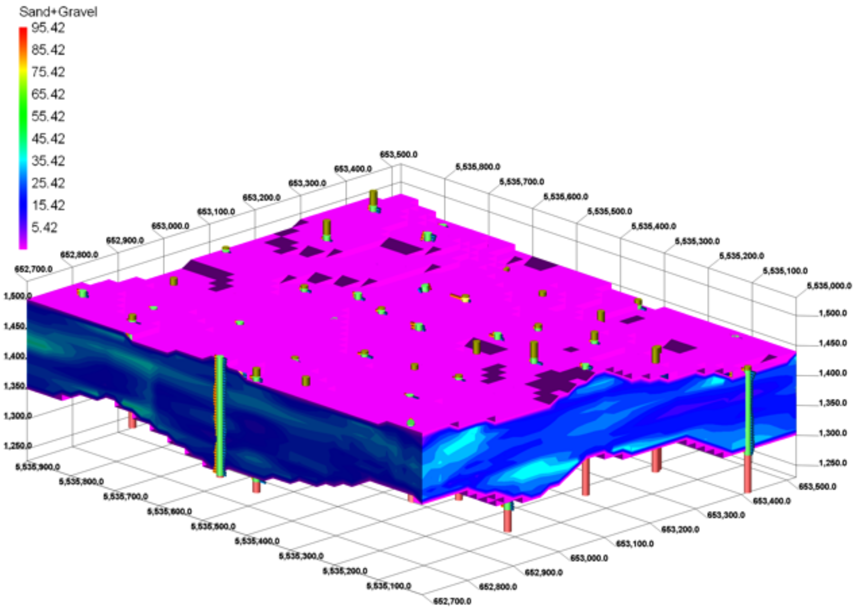


Clay < 20%

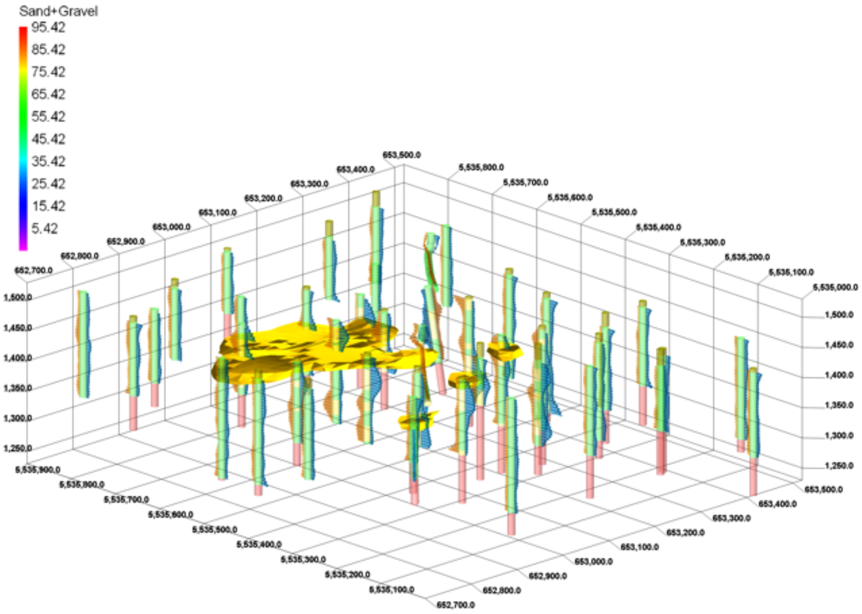
Step 4. The sand and gravel models were then combined by adding each of the block values. The combined model was then filtered to show only those regions where the sand and/or gravel are greater than 80 percent (table 10).

Table 10. Sand + Gravel and (Sand + Gravel) > 80% Models.

Sand > 40%
+
Gravel > 40%

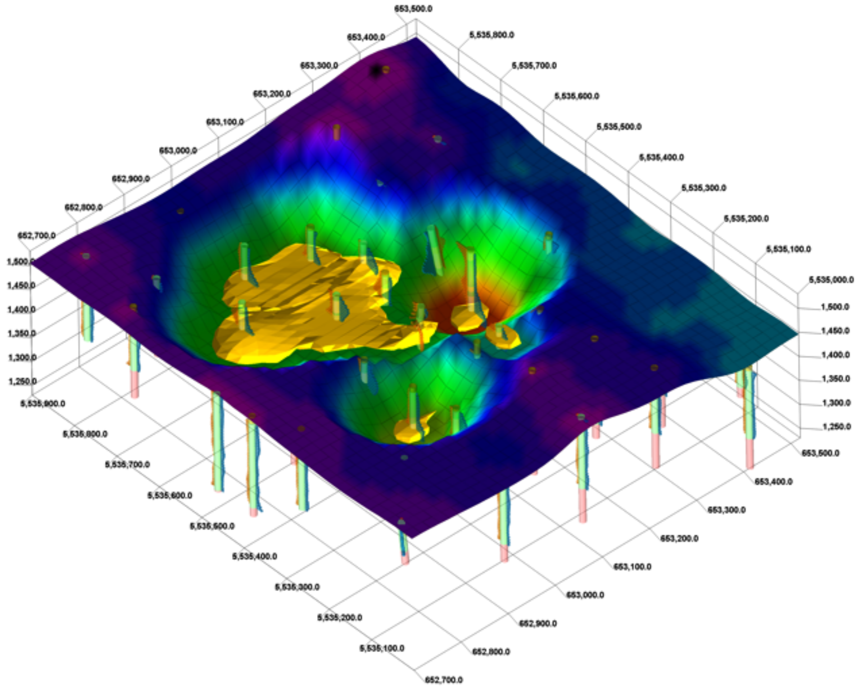
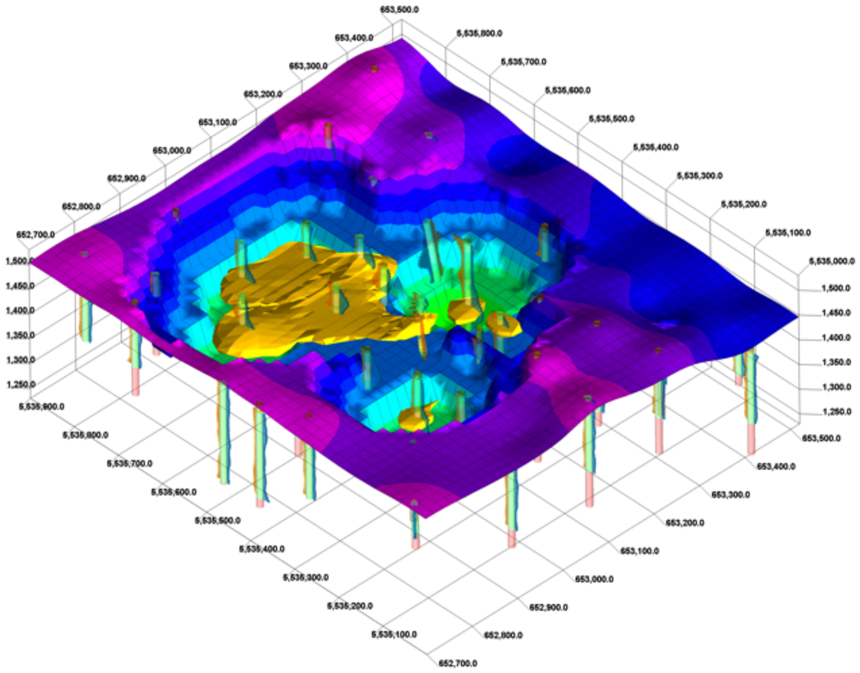


Sand + Gravel
> 80%



Step 5. Finally, a series of pit models were generated (table 11) by using a "floating cone" algorithm that automatically designs a preliminary pit by removing material above the ore based on user-defined criteria (*e.g*. maximum slope, bench height, ore grade, etc.).

Table 11. Preliminary pit designs.

No Benches	
Bench Height = 20 feet	

VISUALIZATIONS (DIAGRAMS)

Diagrams of grids and solids (table 12 and table 13) are more than “eye candy”. They provide a quality-check on two levels: (1) By visually comparing the original data with the interpolated model, a check can be made for the “fidelity” of the model relative to the original data. (2) An overall view of the model should be made to make sure that it's not just pretty and accurate, but that it makes geologic sense.

Table 12. Methods for visualizing grid and block models.

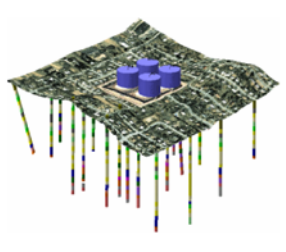
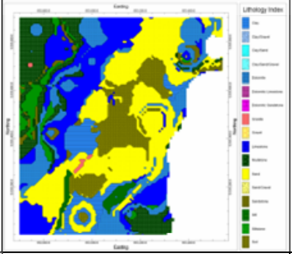
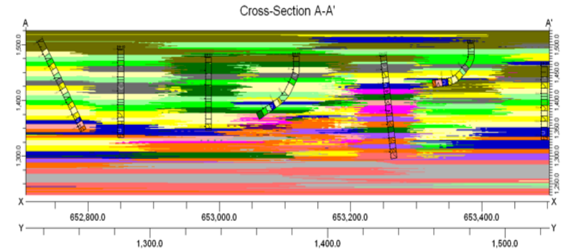
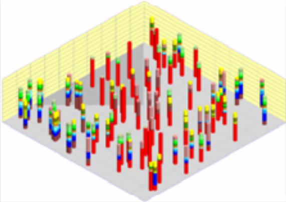
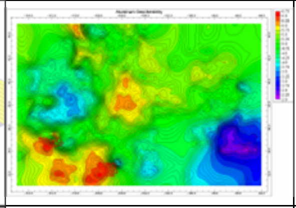
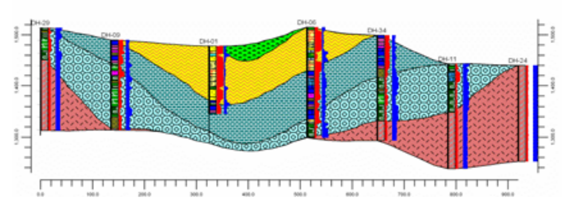
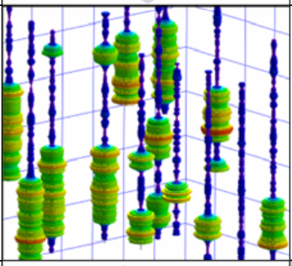
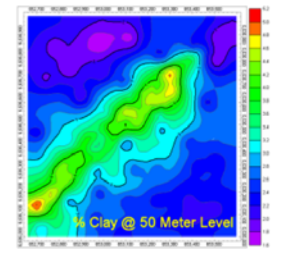
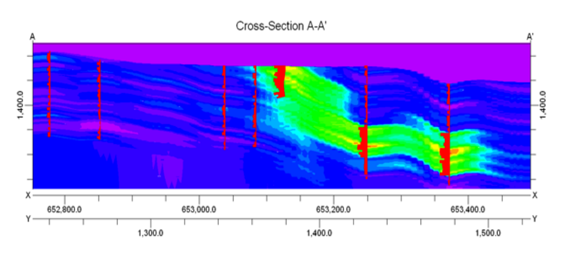
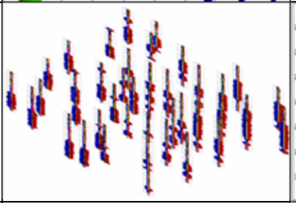
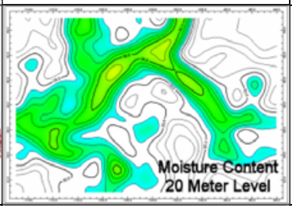
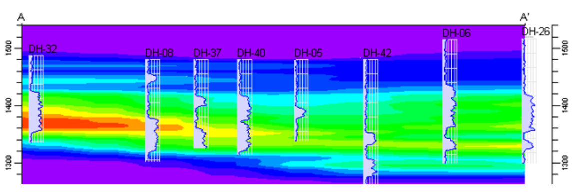
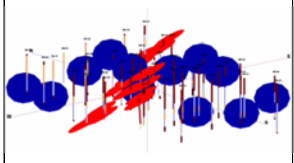
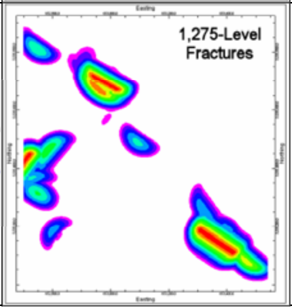
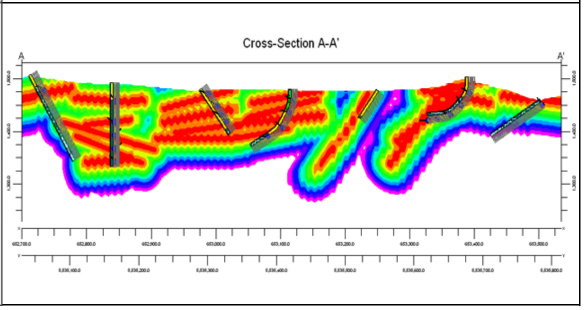
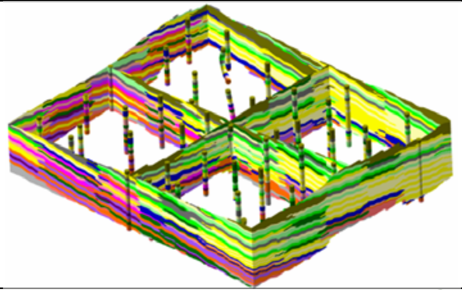
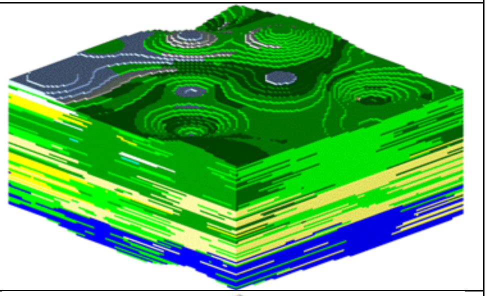
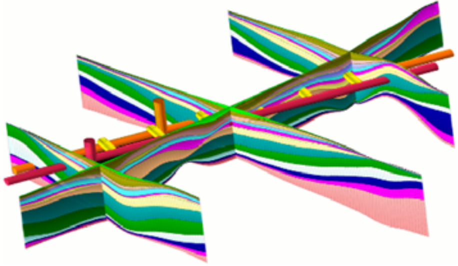
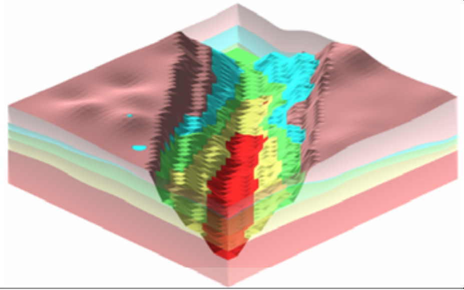
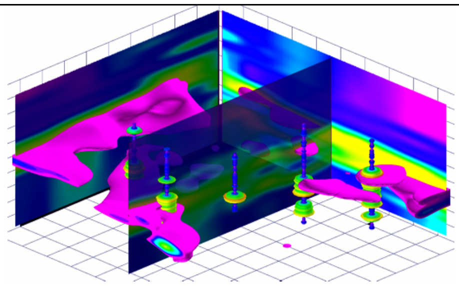
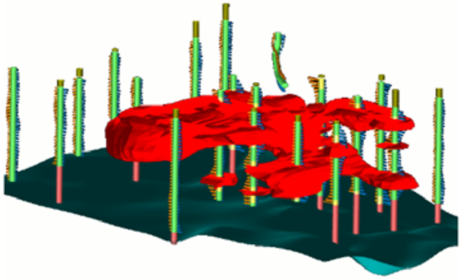
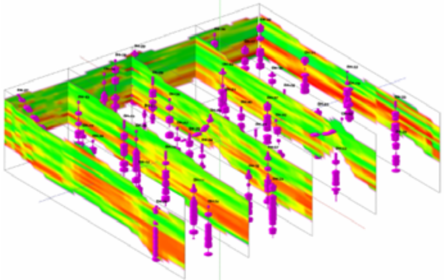
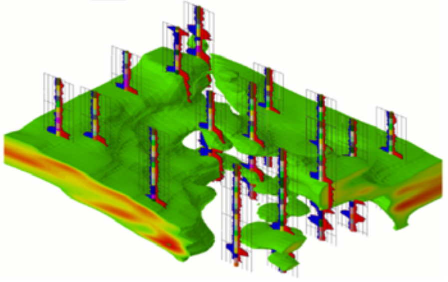
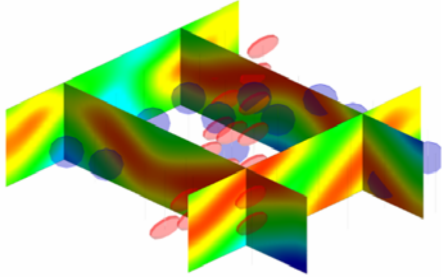
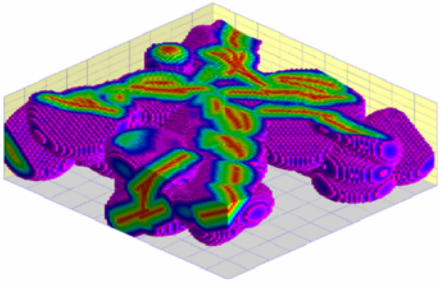
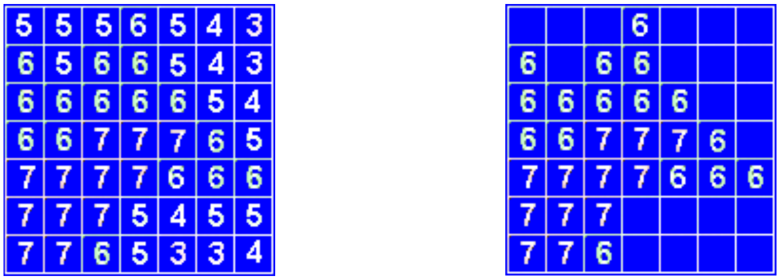
Data Type	Striplogs	Plan-Views	Cross-Sections
Lithology			
Stratigraphy			
Interval-Based Data (Geochemistry)			
Point-Based Data (Geophysics & Geotechnical)			
Fractures			

Table 13. Methods for visualizing grid and block models (continued).

Data Type	Fence Diagrams	Solid Models
Lithology		
Stratigraphy		
Interval-Based Data (Geochemistry)		
Point-Based Data (Geophysics & Geotechnical)		
Fractures		

VOLUMETRIC COMPUTATIONS

Once a grid or block model has been created, computing the volume of ore is accomplished by performing simple mathematical operations with the cell or voxel values. For example, consider a grid model that represents isopach values (in meters) for a clay seam (fig. 8a).



5	5	5	6	5	4	3
6	5	6	6	5	4	3
6	6	6	6	6	5	4
6	6	7	7	7	6	5
7	7	7	7	6	6	6
7	7	7	5	4	5	5
7	7	6	5	3	3	4

A. Grid model representing estimated clay thickness values.

			6			
6		6	6			
6	6	6	6	6		
6	6	7	7	7	6	
7	7	7	7	6	6	6
7	7	7				
7	7	6				

B. Grid model representing estimated clay thickness values greater than five meters.

Figure 8. Unfiltered and filtered grid models representing estimated clay thickness values.

If the thickness values are added together (272 meters) and multiplied by the cell size (50 x 50 meters), a total volume (680,000 cubic meters) is obtained. This volume number is then multiplied by a density conversion factor (1.826 metric tons per cubic meter) to obtain the final tonnage (1,2m metric tons).

$$272 \text{ meters} \times 50 \text{ meters} \times 50 \text{ meters} = 680{,}000 \text{ cubic meters}$$

$$680{,}000 \text{ meters}^3 \times \frac{1.826 \text{ metric tons}}{\text{meters}^3} = 1{,}241{,}680 \text{ metric tons}$$

The total mass can be considered a “geologic reserve”, meaning that this is the total amount of clay within the project area without consideration for any economic factors. To illustrate the addition of an economic constraint to this example, clay thicknesses less than six meters will be removed from the model (fig. 8b).

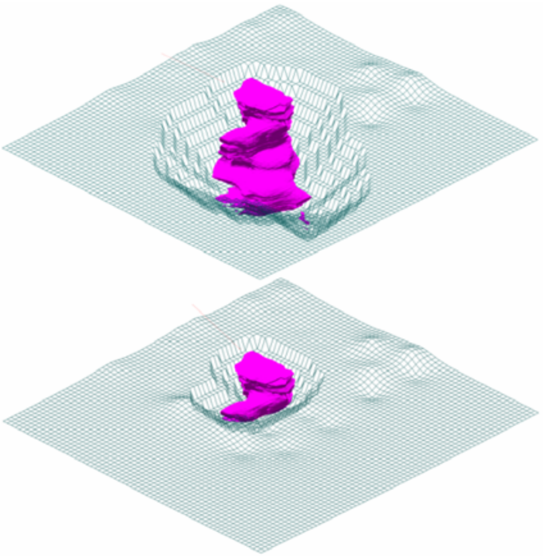
Once again, the thickness values are added together (180 meters) and multiplied by the cell size (50 x 50 meters) in order to compute the total qualified volume (450,000 cubic meters). This qualified volume number is then multiplied by the density conversion factor (1.826 metric tons per cubic meter) to obtain the final tonnage (821,700 metric tons).

$$180 \text{ meters} \times 50 \text{ meters} \times 50 \text{ meters} = 450{,}000 \text{ cubic meters}$$

$$450{,}000 \text{ meters}^3 \times \frac{1.826 \text{ metric tons}}{\text{meters}^3} = 821{,}700 \text{ metric tons}$$

By combining these techniques with the aforementioned multivariate analyses, it is possible to generate volumetrics based on multiple criteria (*e.g.* computing the tonnage in which calcium is greater 75%, and shrinkage is less than 5%, and brightness is greater than 0.8, and so on …).

Other important considerations include optimization based on maximum stripping ratios and maximum bench height. These optimizations employ a "floating cone" technique that essentially projects an inverted cone upwards from each ore-grade voxel. Starting at the base of the model and moving upwards, the floating cone algorithm essentially removes ore-grade voxels in which the combined statistics of the overlying voxels (*e.g.* overburden, interburden, ore ratio) do not meet user-defined criteria (fig. 9).



Initial excavation pit
without optimization.
Stripping Ratio = 5.6

Excavation pit
optimized to
maximum stripping
ratio of 2.8.

Figure 9. Pit optimization.

Interactive three-dimensional diagrams allow the user to combine the raw data (borehole information) with the pit and ore bodies to perform the final, and most important step: Visually comparing the real against the interpolated to make sure that the modeling is reasonable (fig. 10).

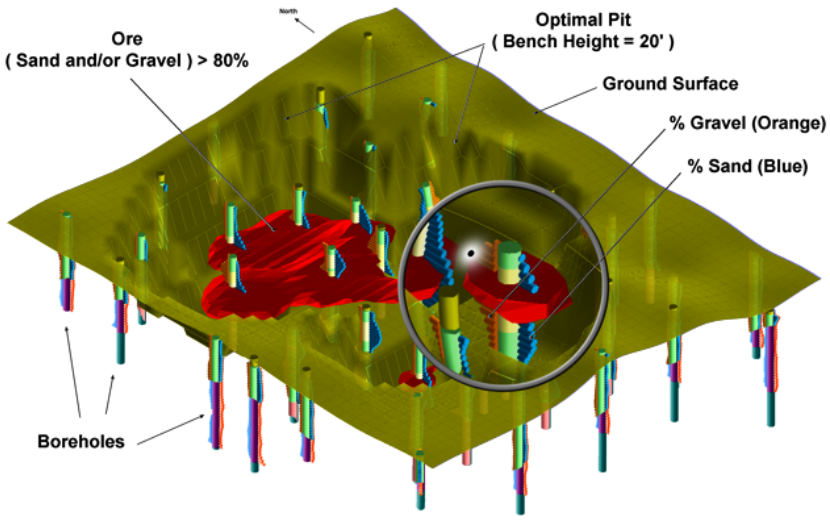


Figure 10. Optimized sand & gravel resource.

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How Can There be Renewable Industrial Mineral Resources?

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ABSTRACT

Decision makers today are concerned about sustainable development, smart growth, and other conservation-minded approaches to mining. Federal and even local programs favor renewable materials and special inducements are commonly offered for buildings or projects that use renewable resources. As a result, categories of raw materials, such as “rapidly renewable”, “renewable”, or “nonrenewable” have been established. Conventional wisdom holds that all mineral resources are nonrenewable, but might some mineral resources renew themselves? If so, products from such special geologic cases should qualify as renewable.

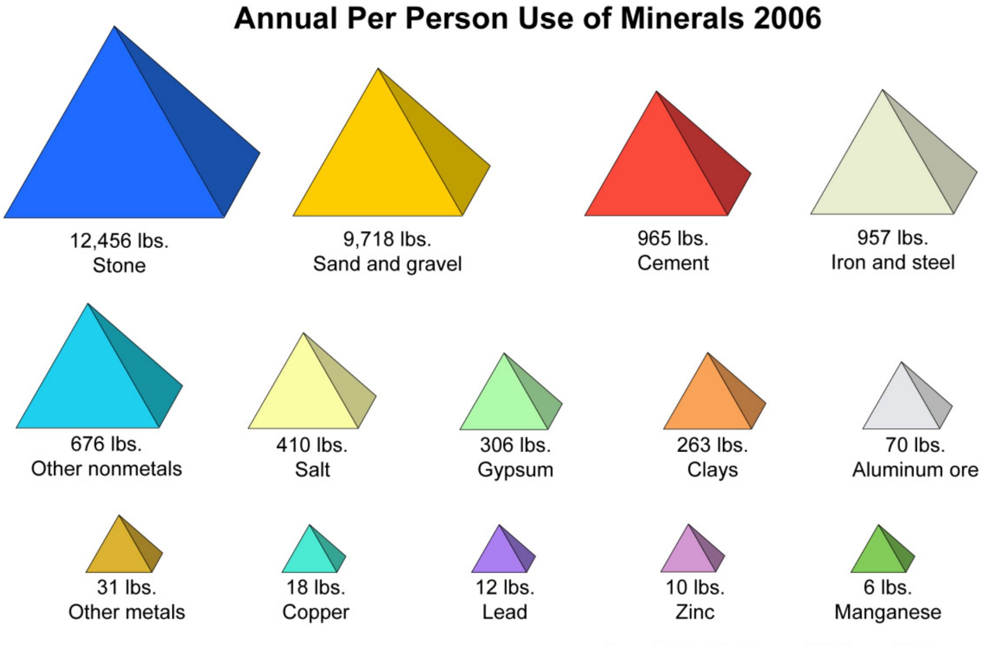
More importantly from the perspective of quantity are sand and gravel deposits, especially those that occur in geologically dynamic settings. Some of these are replenished by actions of running water and occasionally even by the wind. As erosion inevitably proceeds, resistant minerals are generated in prodigious quantities. Every year new sediments are formed and transported in quantities many times greater than the annual amounts used by humans. Some states, such as California, recognize the possibility of renewable sand deposits in their mining regulations. In the heartland, river dredging can take place for long periods as large rivers bring sands to a mineable site. Beach replenishment projects often rely on nearshore sands that have been shown to reform after mining. Much renewable sand is deposited in flood or storm events but longshore drift and other less dramatic action can replenish deposits. Dune sand migrates extensively and while not generally mined in the United States, can be considered a renewable deposit.

Renewable industrial mineral resources do exist. It is important that society understands that some minerals are renewable and that those should be considered as premium “green” building materials to enhance sustainable growth.

INTRODUCTION

Certain minerals can grow continuously and have regrown after mining. Evaporite deposits, especially in arid continental settings, are commonly harvested annually for halite, trona, and other valuable chemical raw materials. In the past, soluble minerals used for gunpowder and other chemicals grew back after being collected from cave settings. Even bog iron deposits have been known to reform, and, doubtless, other examples can be found.

Sand is a common material critical to the manufacture of many modern technological wonders. It occurs everywhere in nature and society. We use millions of tons of sand each year in a multitude of materials and manifestations (fig. 1). Sand use has a long history and a bright future. Fortunately, sand is produced in prodigious amounts by natural processes and distributed widely by geologic agents. Sand is ubiquitous in the natural world, our manmade universe, even in human literature. Who has not had sand in their shoes, known a strong-willed person with "sand" or grit, or heeded biblical advice to avoid building upon shifting sands or modern advice to get one's head out of the sand? This paper will help the reader understand more about sand and, as suggested by turn of the (last) century British poet and artist William Blake, "to see the universe in a grain of sand." This common but vital material that has existed since the beginning of our Earth can even be considered a renewable resource. In this paper, I will outline what sand is, where it originates, some of its many uses, its importance as a natural resource that helps build our society, and its renewable nature.



Source: U.S. Geological Survey and U.S. Bureau of the Census
2006 Data compiled by Kathryn R. Shaffer

Figure 1. Annual per person use of industrial minerals in the United States. Approximately 1.4 billion short tons (1.3 Gt) of sand and gravel are consumed annually. (Bolen, 2007, Dolley, 2007, U.S. Bureau of the Census, 2006).

We are not the first culture to rely on quartz. The very first hominids in Africa used quartz-rich rocks for their tools some 2.5 million years ago. Earliest Americans shaped a variety of quartz called chert into tools for hunting, household chores, and protection (fig. 2). Today quartz rendered into silicon, glass, and chemicals provides the basics of modern communication and computing, as illustrated by the silicon chip (fig. 3). Great quantities of sand are used in the construction industries. Glass production, including fiberglass, requires very pure quartz sand which is melted and can be recycled into other products.

Sand grains are wrought into beautiful and philosophically meaningful mandalas by Buddhist monks or Navajo shamans. Some Buddhist sand paintings emphasize the meaninglessness of time. One such mandala is ironically used on this clock face (fig. 4). After completion these complex icons of nature guided by human intellect and skill are destroyed and cast into a body of water to further emphasize the transience of human existence. The order of the art is gone but the sand remains with its intrinsic character intact just as it behaves in nature.

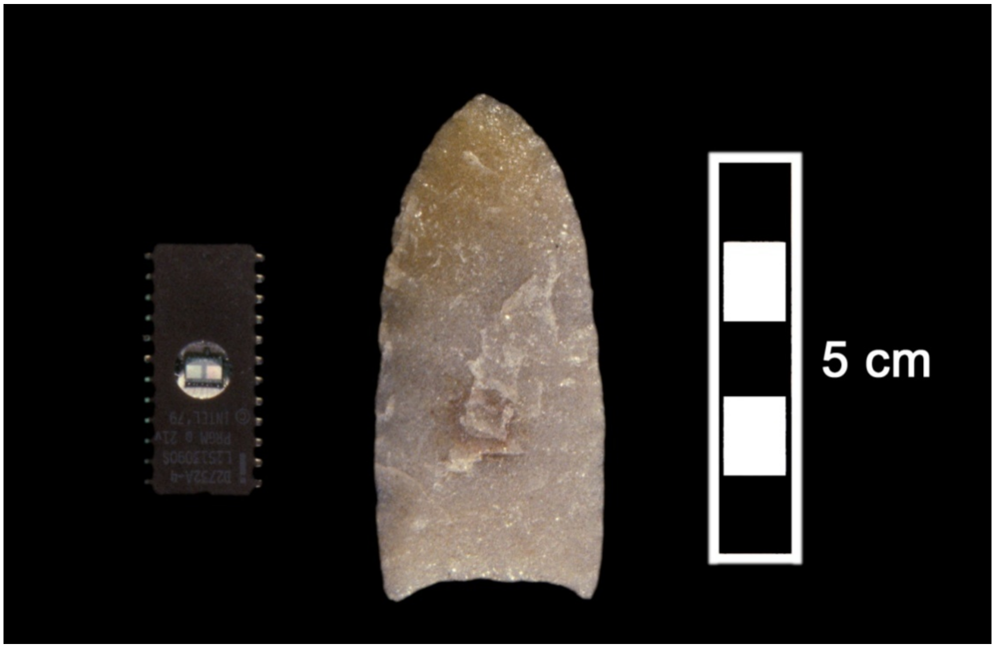


Figure 2. Silicon as chert was used for arrowheads and other early tools.

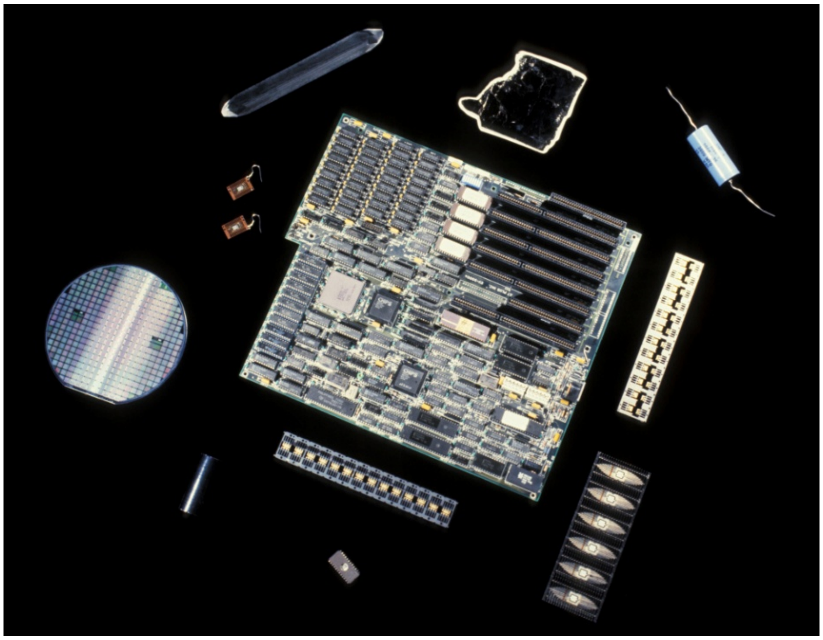


Figure 3. Modern computers contain many forms of silicon derived from manmade quartz. At upper left is a manmade crystal.

Figure 4. Colored grains of sand are used to make fantastic but ephemeral mandalas in Buddhist and other cultures.

What is Sand?

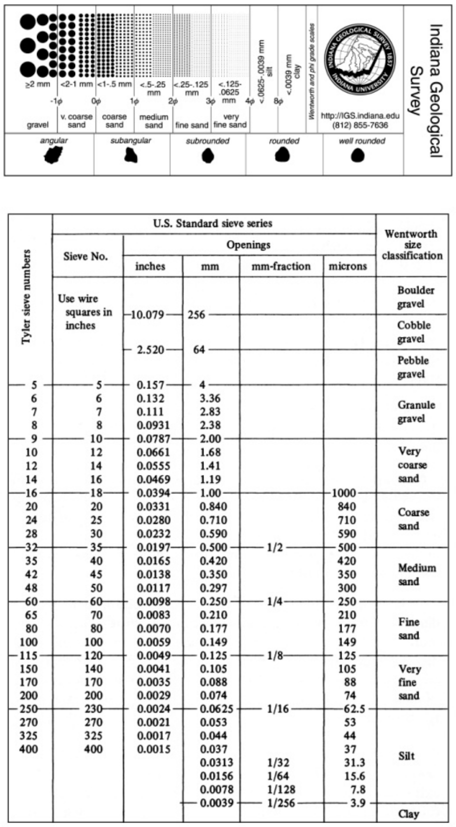
Sand is generally known as loose, gritty particles of worn or disintegrated rock usually deposited along shores of water bodies, in river beds, or desert dunes. Geologists define sand more specifically as a natural loose, granular material made of separate mineral or rock particles ranging from 0.0625 to 2.00 millimeters (mm) in size. Larger particles are granules, pebbles, cobbles, or boulders (>256 mm) and smaller grains are silt (0.0625-0.00 mm) or clay (<0.004 mm). Particle size is measured by passing samples through a series of screens with various size of openings (fig. 5). Sand is a product of weathering and transport of preexisting rocks. Sand and its solidified form, sandstone, are both very important geologic products that have undergone extensive research (Pettijohn, 1975). Publications written for the general public such as "Sand" (Siever, 1988) have also been well received. Forces that produce sand and sand parent materials occur all over the Earth and so sand deposits are found in all parts the globe. Sand grains can be a part of soil, but soil also contains fine-grained; plastic clay minerals; organic materials; oxide minerals; and poorly defined mineraloids.

Sand is the final product of rock weathering (fig. 6), which is an important part of the rock cycle. Sand is created by the weathering of any quartz-bearing rock – igneous, sedimentary, or metamorphic. It is involved in a continuous cycle of rock formation and erosion that started with the Earth's formation and continues today. Weathered grains become separated from intergrown or cemented minerals that make up hard rocks. Grains are transported mainly by water on an oft-interrupted quest for the sea. As they travel, weaker minerals are removed and resistant grains become smaller in size, become more equant or rounded in shape, and their surfaces are modified by constant abrasion or chemical attack. This process is referred to as increased maturity of the sand and is a function of time. Many sand grains are very well rounded indicating several cycles of deposition and transport. Very mature sands make the most chemically pure, most ideally round, and best-sorted sand deposits. Scientists study mineral compositions, grain-size distribution, measures of grain roundness, statistics of particle sorting and other details to unfold a sediment's history. These features are also of critical importance to a sand deposit's suitability for human uses (Carr, 1971; Zdunczyk and Linkous, 1994).

Numerous physical characteristics of sand are measured to help define its origins, histories, and potential uses. The term "sand" is used to define particle size, the quartz-rich sediment, geologic deposits, or a mined product. The United States Geological Survey (USGS) uses several terms interchangeably as reflected in this quote:

> Industrial sand and gravel, often termed "silica," "silica sand," and "quartz sand," includes high SiO_2 content sands and gravels. (Bolen, 1996, p. 715)

Sands can be made of many different minerals but industrial sand deposits are made mainly of the mineral quartz. White tropical beaches can be made of carbonate minerals, while others are composed of green olivine, dark ferromagnesian minerals, resistant black oxide minerals, or whatever minerals are available near the deposit. But almost all important sand deposits are composed of the mineral quartz with varying types and amounts of other minerals.



Tyler sieve numbers	U.S. Standard sieve series					Wentworth size classification
	Sieve No.	Openings				
		inches	mm	mm-fraction	microns	
	Use wire squares in inches					Boulder gravel
		10.079	256			Cobble gravel
		2.520	64			Pebble gravel
5	5	0.157	4			Granule gravel
6	6	0.132	3.36			
7	7	0.111	2.83			
8	8	0.0931	2.38			
9	10	0.0787	2.00			Very coarse sand
10	12	0.0661	1.68			
12	14	0.0555	1.41			
14	16	0.0469	1.19			
16	18	0.0394	1.00		1000	Coarse sand
20	20	0.0331	0.840		840	
24	25	0.0280	0.710		710	
28	30	0.0232	0.590		590	
32	35	0.0197	0.500	1/2	500	Medium sand
35	40	0.0165	0.420		420	
42	45	0.0138	0.350		350	
48	50	0.0117	0.297		300	
60	60	0.0098	0.250	1/4	250	Fine sand
65	70	0.0083	0.210		210	
80	80	0.0070	0.177		177	
100	100	0.0059	0.149		149	
115	120	0.0049	0.125	1/8	125	Very fine sand
150	140	0.0041	0.105		105	
170	170	0.0035	0.088		88	
200	200	0.0029	0.074		74	
250	230	0.0024	0.0625	1/16	62.5	Silt
270	270	0.0021	0.053		53	
325	325	0.0017	0.044		44	
400	400	0.0015	0.037		37	
			0.0313	1/32	31.3	
			0.0156	1/64	15.6	
			0.0078	1/128	7.8	
			0.0039	1/256	3.9	Clay

Figure 5. Sieves define sand sizes. Shapes of grains are also important.

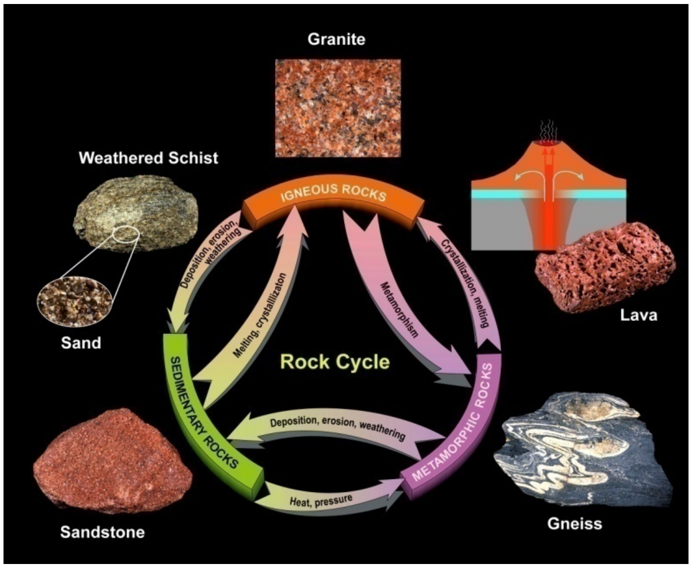


Figure 6. Rocks are formed from minerals. They undergo constant recycling through the rock cycle.

SAND ON THE MOVE

Weathering and Transport

The mineral mosaics of rocks degrade and fall apart once subjected to surface conditions that mount a complicated assault of chemical and physical forces collectively known as weathering. Temperature changes, wetting and drying, sunlight, microorganisms, and most importantly, freezing and thawing of ice or crystallization of other minerals produce repeated mechanical forces that force originally interlocking mineral grains apart. Chemical reactions, especially those involved with water, further liberate and modify mineral grains. Weathering is especially severe in high mountains. Over time, high mountain ranges are virtually flattened by weathering (Ritter, 1986).

Rock and mineral fragments, once liberated from their igneous or metamorphic origins, move by gravity, ice, water, and even air currents toward the lowest points on Earth, usually the sea floor. Erosion and transport of grains result in destruction of physically weak minerals as they cascade down mountains, crash into boulders, and grind against each other. The constant jostling reduces sizes of mineral grains, grinds off corners, and eliminates unstable or weaker minerals. The aggregate of weathered and transported grains are called sediments.

Sediments, like humans, reflect the rigors of their experiences. Mineral grains that have traveled far have more refined compositions, shapes, sizes, and companions. Mature sediments are those that have long experience in traveling. Silica sand deposits are usually mature or supermature. Geologists employ sophisticated measurements to characterize sediments. One of the most common is grain size, which is determined by the screening process discussed earlier. Natural deposits contain a range of shapes and grain sizes from fine (fig. 7) to coarse (fig. 8).

Particles that are immature generally are angular in shape (fig. 9), but they become more rounded with transport and maturity. Many sand consumers prefer very round grains (fig. 10) because they flow easily and react completely, but for some uses such as foundry molds, angular grains are preferred because they form a more stable body. Abrasive producers also prefer angular sands. More mature sands are well sorted, meaning that they have a relatively limited size range; sedimentologists use sophisticated statistics to quantify size, angularity, and sorting of grains.

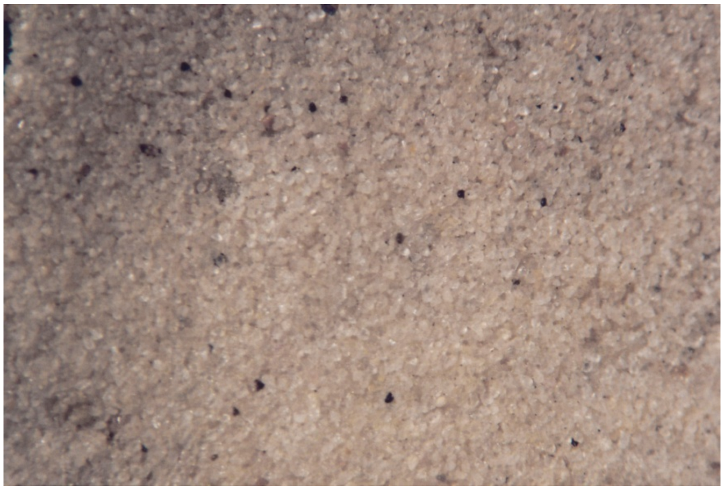


Figure 7. Fine-grained quartz sand. These grains are approximately 0.01 in (0.25 mm) in diameter.

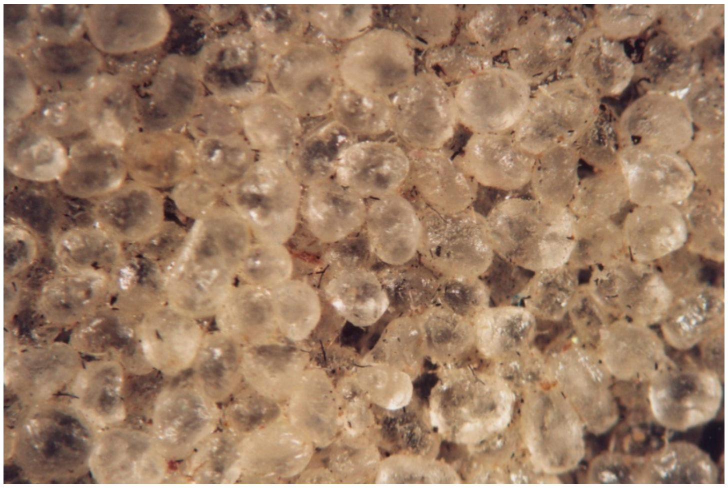


Figure 8. Coarse-grained quartz sand. These grains are approximately 0.04 in (1 mm) in diameter.

Figure 9. Immature sediment with angular fragments, mixture of sizes, various minerals, even mineral fragments.

Figure 10. Pure, well-rounded, and sorted quartz grains are especially valued.

Mature sands tend to be made dominantly of one mineral, quartz. Younger sediments often contain relatively unstable minerals such as mica or feldspar or even individual rock fragments containing several different minerals. Very long travel times or multiple transport events can lead to deposits of remarkable purity. Supermature sands often are more than 95 percent quartz with some natural deposits containing 98 percent quartz. These high-purity sands have many economic applications and are required for glass manufacture (table 1).

Sediments deposited by glaciers are almost never pure enough nor of proper sizes to be used as industrial sands but most can be used for construction purposes. Moving water or air are great media for sorting and refining raw sand materials.

Table 1. Specifications for the chemical composition of glass sand, from Carr (1971).

Quality	SiO_2 Minimum (percent)	Al_2O_3 Maximum (percent)	Fe_2O_3 Maximum (percent)	CaO + MgO Maximum (percent)
First quality, optical glass	99.8	0.1	0.020	0.1
Second quality, flint glass containers and tableware	98.5	0.5	0.035	0.2
Third quality, flint glass	95.0	4.0	0.035	0.5
Fourth quality, sheet glass, rolled and polished plate	98.5	0.5	0.060	0.5
Fifth quality, sheet glass, rolled and polished plate	95.0	4.0	0.060	0.5
Sixth quality, green glass containers and window glass	98.0	0.5	0.300	0.5
	95.0	4.0	0.300	0.5
Seventh quality, green glass	98.0	0.5	1.000	0.5

Eighth quality, amber glass containers	95.0	4.0	1.000	0.5

Stops Along the Way

Rivers, waves, long shore currents, and winds are the most efficient movers of sediments. Large particles move by being pushed along the bottom of a stream as bedload by river currents and grains of a certain size move by bounding or saltation. Very fine materials can be suspended in turbulent waters as evidenced by muddy rivers (fig. 11A). Sediment sizes that can be transported depend on fluid velocity, turbulence, viscosity, and roughness of the bottoms. Sand grains can move in suspension constantly floating in air or water currents, by traction (slipping along the bottom) or a process called saltation where grains bounce along (fig. 11B). Many times sand congregates into ripples in water or dunes if on land. In ripples or dunes, sand goes up a gently sloping backside and cascades over the top onto a steep leeward slope or slip face. These forms move and change as fluid motion changes. Huge amounts of quartz sediments move from the land to the sea with billions of tons deposited in seas each year.

As fluid velocity slows upon entering quiet water, sediments may cease traveling, fall to the bottom, and become deposited, at least temporarily. Rivers have complex water motions and sand deposits are constantly being reworked, moved, and redeposited. Rivers meander sideways across their floodplains (fig. 11C) generating wide sheets of sand deposits or downcut, leaving terrace deposits at levels high above current water level. Sand and gravel are often mined along rivers or even in active channels. Some sand mining relies on continuous renewal of deposits by traveling sediments. Finally, rivers build large deltas of sands into lakes or oceans. Deltas grow as long as sediment is brought by rivers, but even large deltas can die if the river changes path.

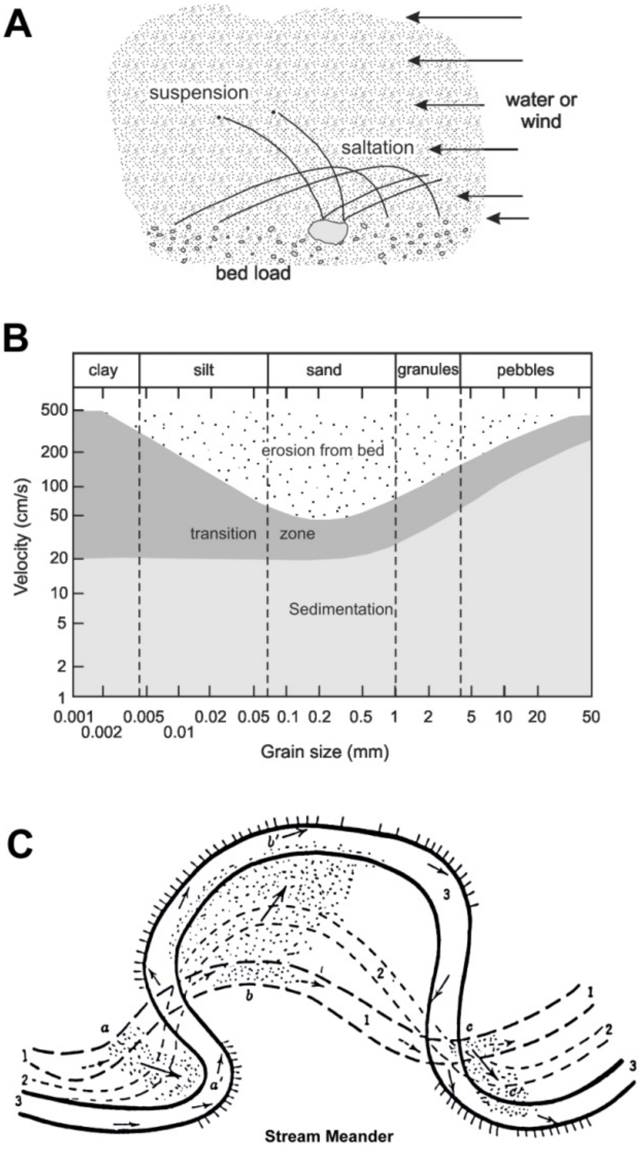


Figure 11. A) Sediments move as bed load by sliding and jumping by saltation, or are continuously suspended. B) Velocity of fluids is an important factor in moving grains. Velocity can also affect river bottoms and cause erosion. C) Rivers themselves move sideways by meandering leaving sand deposits lateral to the river or by downcutting, leaving terraces above the current river.

Once deposited in a water body, sand still moves either through wave motion or wave-generated long shore drift. When waves hit a beach at an angle, sand is forced sideways along the coast and broad beaches are built or destroyed by so-called long shore currents that move “rivers of sand.” Large storms can completely obliterate beaches, offshore shoals, or even entire islands. Offshore mining, manmade structures, or dredge projects dramatically affect ocean sand movement. Governments routinely commit tens of millions of dollars to dredge sand from shipping channels, to replenish sand beaches, or make sand bypassing projects in order to preserve structures and protect recreation industries. Underwater sand mining is common on coasts throughout the world and some mining companies find that sand is noticeably replenished by natural sand movement sometimes in periods as short as a year or two.

In high, cold mountains and rarely on low-lying planes, glaciers made of ice move sediments; however the ice movement itself does almost no sorting of grains and so rarely produces sand deposits. Meltwaters rushing from dying glaciers often rework sediments of all sizes, winnowing away fine-grained clays or silts and leaving well-graded sand deposits (fig. 12) along their paths.

Sediments spend a lot of their travel time in river-related deposits but some are also stopped in lake deposits. Waves often form well-sorted deposits along lakeshores as do winds that form dune fields. In the eastern and midwestern United States unconsolidated sand deposits are almost all related to rivers, meltwater channels, lake deposits, or dunes. Rivers and lakes are generally short lived and most sediments ultimately reach the ocean.

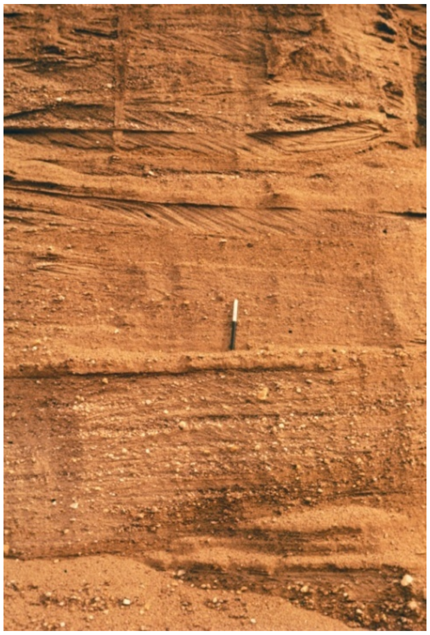


Figure 12. Well-sorted bedded sand with minor gravel reflects good sorting by water movement.

By the Sea

Once the energy of movement is spent, grains fall by gravitational settling to the lake floor or sea bed to form large deposits of sands. Larger fragments settle first near shore while fine-grained and platey clay grains can travel far to sea. At the edge of the coast wave motion and long shore currents winnow and transport huge amounts of sand, often sorting by size and specific gravity.

Once sand grains reach the ocean their travels do not cease. Sediments build up near river mouths often in deltas, but much material is moved along the shore by wave action and a process called long shore drift. Normal long shore currents created by everyday wave motion move sand constantly, but very dramatic changes are wrought by strong storms that can obliterate barrier islands and redistribute enormous quantities of sand reshaping islands, beaches, shoals, and many minor nearshore deposits. Waves, currents, and drift build beaches, barrier islands, offshore shoals, spits, dunes, and many coastal deposits from sand. These features are mutable as any beach lover knows. Entire islands are worn away and deposited elsewhere. Inlets through islands or shoals form and man builds a variety of facilities along the coast. Table 2 summarizes selected data about beach sediment movement.

Table 2. Longshore sediment transport rates at various coastal sites, from Johnson (1956).

Location	Transport Rate (m^3/yr)	Predominant Direction	Years of Record
U.S. Atlantic Coast			
Suffolk Co., N.Y.	255,000	W	1946 – 1955
Sandy Hook, N.J	377,000	N	1885 – 1933
Sandy Hook, N.J.	334,000	N	1933 – 1951
Asbury Park, N.J.	153,000	N	1922 – 1925
Shark River, N.J.	255,000	N	1947 – 1953
Manasquan, N.J.	275,000	N	1930 – 1931
Barnegat Inlet, N.J.	191,000	S	1939 – 1941
Absecon Inlet, N.J.	306,000	S	1935 – 1946
Ocean City, N.J.	306,000	S	1935 – 1946
Cold Springs Inlet, N.J.	153,000	S	--
Ocean City, Md.	115,000	S	1934 – 1936
Atlantic Beach, N.J.	22,600	E	1850 – 1908
Hillsboro Inlet, Fla.	57,000	S	--
Palm Beach, Fla.	115,000 – 172,000	S	1925 – 1930
Gulf of Mexico			
Pinellas Co., Fla.	38,000	S	1922 – 1950
Perdido Pass, Ala.	153,000	W	1934 – 1953
Galveston, Texas	334,700	E	1919 – 1934
U.S. Pacific Coast			
Santa Barbara, Calif.	214,000	E	1932 – 1951
Oxnard Plain Shore, Calif.	756,000	S	1938 – 1948
Port Hueneme, Calif.	382,000	S	1938 – 1948
Santa Monica, Calif.	207,000	S	1936 – 1940
El Segundo, Calif.	124,000	S	1936 – 1940
Redondo Beach, Calif.	23,000	S	--
Anaheim Bay, Calif.	115,000	E	1937 – 1948
Camp Pendleton, Calif.	76,000	S	1950 – 1952
Great Lakes			
Milwaukee Co., Wis.	6,000	S	1894 – 1912
Racine Co., Wis.	31,000	S	1912 – 1949
Kenosha, Wis.	11,000	S	1872 – 1909
Ill. State Line to Waukegan, WI	69,000	S	--
Waukegan to Evanston, Ill.	44,000	S	--
South of Evanston, Ill.	31,000	S	--
Outside of the U.S.			
Monrovia, Liberia	383,000	N	1946 – 1954
Port Said, Egypt	696,000	E	--
Port Elizabeth, South Africa	459,000	N	--
Durban, South Africa	293,000	N	1897 – 1904
Madras, India	566,000	N	1886 – 1949
Mucuripe, Brazil	327,000	N	1946 – 1950

Beaches are where the land meets the oceans. These areas make up less than 1 percent of Earth's land mass, but are incredibly important because almost half of the entire human population lives within 60 miles of a coast. Commerce, shipping, and recreation require relatively stable coasts and huge amounts of money and effort are spent on fighting the effects of sand movement. Sand grains have been shown to move several kilometers in just one day. Huge volumes of sand travel naturally and millions of tons of sand are rearranged by coastal engineers to keep channels open, to stabilize beaches, or shore up facilities each year.

Sand was often mined from beach areas in the past. This activity still occurs in many countries but very rarely in the United States. Most mining of sand from the sea is done from offshore deposits. Extensive research on such mining has shown that mined areas often fill in with new sand, sometimes in a period of years under normal conditions. Hurricanes, large storms, and other natural disasters can mobilize sand in unimaginable quantities.

Sand in the Air

Where abundant sand materials, dry conditions, and sufficient wind combine, sands will be deposited by air currents in dune forms. Some of these areas are known as sand seas and cover thousands of square kilometers. Wind is an especially good agent for sorting fine sand grains. Some of the dunes can be hundreds of meters high. These dunes move with the wind, sometimes at fast rates. Builders often wage war with encroaching sand. One study showed dune migrations of 3.8 to 7.5 miles (6.1 to 12.1 km) per year (Tsoar and others, 2004). This represents a huge amount of sand movement over a large area and could easily replenish mined areas.

Frequently sand is piled up in dunes landward of beaches by wind action. Inland dunes are formed by strong directional winds that transport sand in generally arid areas. Some of the most pure sands are found in dunes and dune-sand mining used to be common. In the United States, mining of sand dunes is severely restricted, but dune mining still occurs in many parts of the world. One of the concerns about dunes is that they move as the wind blows. Large inland areas of dunes such as Algodones Dunes, Imperial Dunes, or the Sahara, march along overtopping vegetation, oases, buildings, and everything in their paths. Desertification by dune movement can cause severe disruptions to human activity, but it also shows the Earth's ability to replenish sand deposits.

Sand Uses

Silica sand is a very important raw material for many modern materials. The main use is for making glass (>35 percent). Different kinds of glass require different levels of purity and grain size (table 3). Glass fiber used for reinforcing, insulation, and textiles are made of very pure silica. Special materials such as fiber optic cables require exceptionally pure sands.

Table 3. Physical and chemical specifications of special-purpose sands, from Carr (1971).

Sand Uses	Physical Properties			Chemical Properties			
	Size Range of Particles (U.S. Standard)	Roundness of Particles	Desirable Degree of Sorting	Percentage Range SiO_2	Percentage Range Al_2O_3	Percentage Range Fe_2O_3	Others
Abrasives:							
Blasting	4 to 100	Round or angular	Well sorted	High	Low	Low	Low in debris
Scouring powder	Silica flour; 99 % less than 200 sieve	Angular or subangular	Well sorted	High	Very low	Very low	Very low; whiteness important
Stone sawing	30 to 100	Round or angular	Well sorted	High	Low	Low	Low in soft particles and materials that stain
Glass and chemical:							
Glass	30 to 140	Round to angular	Moderately well sorted	Very high	Low	<1%	<0.5 %
Porcelain	30 to 140	Round to angular	Moderately well sorted	Very high	Low	<1%	Low
Silicon carbide	20 to 100	Round to angular	Moderately well sorted	>99.0%	Low	Low	Low
Sodium silicate	20 to 100	Round to angular	Moderately well sorted	>99.3%	<0.25%	<0.35%	Low
Metallurgical:							
Metallurgical pebble	3/8 in. to 8 in.	Round to angular	Moderately well sorted	Very high	<0.4%	<0.2%	Base oxides, <0.3%; phosphorus and arsenic not permitted
Refractory:							
Core	30 to 140	Round to angular	Moderately well sorted	High	Low	Low	Low in debris
Furnace bottom	3 to 200	Round to angular	Moderately sorted	High	Some desirable	--	--
Ganister mix	50 to 200	Round to angular	Moderately sorted	High	Some desirable	--	--
Molding	70 to clay	Round to angular	Moderately sorted	Variable	Variable	--	--
Refractory pebble	40 to 2 in.	Round to angular	Moderately sorted	High	<0.4%	<0.4%	Opaline silica, <0.5 % ; CaO, <1.0 %; alkalies, <0.5 %; TiO_2, very low
Miscellaneous:							
Engine	16 to 100	Angular to subangular	Well sorted	High	Low	Low	Low in debris
Filtering							
Water filtering	3/32 to 3½ in.	Round to subround	Well sorted	High	Low	Low	--
Sewage trickling	1 in. to 3 in.	Round to subround	Well sorted	High	Low	Low	--
Sludge filtering	4 to 50	Round to subround	Well sorted	High	Low	Low	--
Hydraulic fracturing	4 to 70	Round	Well sorted	>98%	Low	Low	Clay, silt, and soft-particle content <0.5 %

Nature first made mineral glass in volcanoes, but man made glass in Mesopotamia more than 4,000 years ago. It was prized by Egyptians, Romans, and other early cultures, but glassmaking was perfected in Europe during the twelfth century. Modern glassmaking is a multibillion dollar industry based on quartz sands. Mineral or glass wool is the leading thermal and acoustic insulating material. Unlike glass wool, mineral wool is made of igneous rock such as basalt and fluxing agents melted at 1,400 to 1,600°C. Glass wool or fiberglass is made of silica sand with other raw or natural material. The raw material is melted at about 1,100°C and made into fibers by forcing the melt through centrifugal spinners aided by jets of air or steam. Many fiberglass plants are in the eastern United States with clusters in Georgia and Alabama; production also occurs in Texas, Kansas, and California. Fiberglass is an environmentally friendly material, which is easily made and readily recycled; it is essential for energy conservation, and is made mostly from an abundant, renewable mineral resource – sand.

Pure quartz sands are known as industrial sand, silica sand, high-quartz sand, or simply "silica" by industries. Carefully sized quartz sand is used extensively for filtering water. Raw, angular quartz sand is mixed with clays to make heat-resistant molds or cores for casting metal parts. Fine sand is used for precision coatings such as jewelry, high-precision parts, or dental devices. Ceramic items depend on quartz for toughness and resilience and for their glazes. Quartz is used to make refractory (temperature-resistant) bricks for lining furnaces and fused quartz can be made into many complex shapes for laboratory devices.

Refined quartz produces a huge range of silicon chemicals used in drugs, cleaners, pharmaceuticals, and the silicon chips that power our computerized world. Quartz provides silicon metal or ferrosilicon, which is an alloying agent for various metals. Silicon carbide, an important abrasive made from quartz and natural quartz, both have been used for myriad abrasives such as sandpaper. Quartz sand is used as a filler or extender for such products as paints, plastics, gels, and other suspensions. It imparts considerable toughness to rubber or plastics, and can provide some temperature resistance. Coarse, spherical sand grains introduced into oil-bearing geologic formations increase permeability of certain rock units by propping open fractures, thus allowing for easier and more complete production of oil. Quartz has use in farming, forestry, and animal husbandry for soil conditioning, as a carrier for farm chemicals, and as additives for animal feed. Quartz sand is even used in recreation such as golf, volleyball, and other sports. In short, we depend on quartz every bit as much as our ancient ancestors and probably even more because of its importance in chemicals and computers. Table 4 summarizes these uses.

Table 4. Industrial sand and gravel sold or used by United States producers in 2004, by major end use[1] modified from Dolley, 2004.

Major Use	Quantity (thousand mt)	Value (thousands)	U.S. Total Value[2] (dollars per ton)
Sand:			
Glassmaking:			
Containers	4,560	$77,900	$17.08
Flat, plate and window	3,410	57,400	16.84
Specialty	817	19,600	23.95
Fiberglass, unground	1,040	17,300	16.64
Fiberglass, ground	696	28,300	40.62

Foundry:			
Molding and core, unground	5,360	83,600	15.61
Molding and core, ground	(3)	(3)	77.61
Refractory	186	4,070	21.84
Metallurgical:			
Silicon carbide	(3)	(3)	29.70
Flux for metal smelting	19	134	7.10
Abrasives:			
Blasting	784	27,400	34.91
Scouring cleaners, ground	(3)	(3)	46.78
Sawing and sanding	(3)	(3)	37.32
Chemicals, ground and unground	771	17,100	22.17
Fillers, ground, rubber, paints, putty, etc.	462	31,100	67.28
Whole grain fillers/building products	2,460	70,900	28.89
Ceramic, ground, pottery, brick, tile, etc.	192	10,600	55.16
Filtration:			
Water, municipal, county, local	410	17,500	42.73
Swimming pool, other	64	4,310	66.96
Petroleum industry:			
Hydraulic fracturing	3,280	135,000	41.26
Well packing and cementing	165	7,890	47.72
Recreational:			
Golf course, greens and traps	887	16,900	19.07
Baseball, volleyball, play sand, beaches	240	5,770	24.08
Traction, engine	137	2,680	19.60
Roofing granules and fillers	266	6,230	23.41
Other, ground silica	XX	XX	XX
Other, whole grain	XX	XX	XX
Total or average	28,700	668,000	23.31
Gravel:			
Silicon, ferrosilicon	570	9,840	17.27
Filtration	55	2,320	42.22
Nonmetallurgical flux	W	W	9.20
Other uses, specified	447	4,410	9.87
Total or average	1,070	16,600	15.47
Grand total or average	29,700	685,000	23.03

W Withheld to avoid disclosing company proprietary data; for sand, included with “Other, ground silica” or “Other, whole grain;” for gravel, included with “Other uses, specified.”

XX Not applicable.

-- Zero.

[1] Data are rounded to no more than three significant digits, except for values per metric ton; may not add to totals shown.

[2] Calculated by using unrounded data.

[3] Included with “Total or average”

Sand Production

The U. S. Geological Survey states that

> Identified resources of silica sand are virtually inexhaustible, and reserves are very large in relation to demand. Known deposits can satisfy national demands at reasonable cost for centuries. (Ketner, 1973, p. 579)

Sand deposits occur under many geographic and geologic conditions. Industrial sands are less common than construction sands and may require more exploration. Geologists find deposits by searching existing records or air photos, then drilling, trenching, sampling, and analyzing samples to confirm a deposit's extent and character. Common sand is produced from unconsolidated deposits or hard, consolidated rocks. Sandstones and quartzites are the most common hard rock sources, but a few operations produce specialty quartz from igneous rocks.

Figure 13 shows industrial sand and gravel production for the United States. The United States produced 32.7 million short tons (st) (29.7 million metric tons [Mt]) in 2004 at a value of $685 million. Worldwide production was 127 million st (115 Mt). The United States produces nearly 30 percent of total world production from more than 150 operations and about three-fourths of production is from the central United States (Dolley, 2004a). Silica-sand production has averaged 31 million st (28 Mt) per year for several years and the average dollar price per ton has risen from $19.58 per metric ton in 2000 to $22.28 per metric ton in 2004. Employment in silica-sand mining stands at about 1,400 and major producing states are Illinois, Texas, Michigan, Wisconsin, North Carolina, California, New Jersey, and Oklahoma. The United States supplies all its glass sand needs and even exports minor amounts of sand. Slovenia, Germany, Belgium, France, Spain, Australia, Japan are also major producers (Dolley, 2004a, 2004b).

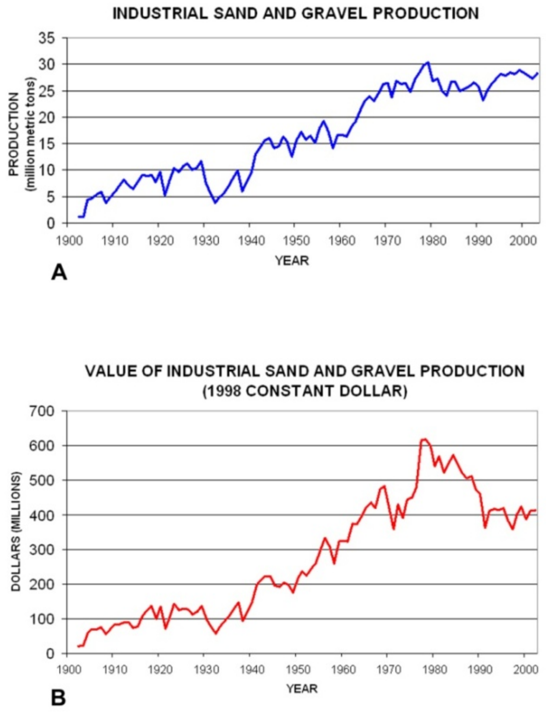


Figure 13. Industrial sand and gravel production (A) and value (B) has been stable or growing slightly for many years in the United States.

Most silica-sand production is from unconsolidated units but the St. Peter Sandstone (Ordovician) and Ottawa Supergroup of Illinois, the Oriskany Sandstone (Devonian) in New York, and the Oil Creek Formation (Ordovician) in Oklahoma are major bedrock producing-units. Identified resources of silica sand are nearly inexhaustible according to the USGS (Ketner, 1973). Glass sand deposits of North America were reviewed by E. William Heinrich, who emphasized the diversity of geologic occurrences and ages of these deposits, especially consolidated rocks (Heinrich, 1981). Known deposits could satisfy U. S. needs for centuries. World resources are similarly immense. U. S. and worldwide natural sand resources are more than adequate to supply current and projected needs. Modern processing can upgrade marginal deposits.

Renewable Sand Resource

Most people do not consider minerals as renewable but there are special cases in which certain resources do reform after mining. In the Great Salt Lake and other southwestern saline lakes, evaporate minerals such as halite continuously grow from evaporation of water (J. W. Gwynn, oral commun., 2007). Early American colonists extracted iron from concentrations of iron minerals known as bog iron which formed in swampy areas. These bog ores could be reharvested every few years (Wayne, 1970). Settlers in the Midwest often extracted nitrate minerals such as saltpeter from cave deposits which grew anew after mining (George, 2005). Even earlier Native Americans harvested sulfate minerals such as epsomite and even aragonite from cave deposits that reformed quite rapidly. Quartz sands, at least those in unconsolidated deposits, can be considered a renewable, even rapidly renewable resource in certain cases (Federal Register, 1995, p. 50724). Renewal of quartz-sand deposits depends on chemical and physical processes that free quartz by weathering.

Geologists measure the combined effects of weathering as denudation rates, reported as average thickness of rocks removed in millimeters per year. Values range from less than 0.5 inch (in) to more than 1 in (<1 mm to >20 mm) per year and are highly variable depending on climate, rock type, topography, and land use. Because of the large areas involved immense amounts of material are continually being removed from the parent rock. Once liberated as fragments or individual mineral grains, weathered materials become sediments that are transported by rivers, glaciers, even the air.

Sediment transport or sediment discharge rates measure amounts of sediment moved in a given time and are measured by weight or volume of sediment that passes a section of stream or discharges into the ocean. Hay (1988) reviewed sediment transport and concluded that rivers supply about 22 x 10^9 st (20 x 10^9 metric tons [mt]) of detrital sediments to the oceans each year or about 0.416 pounds (lb)/square yard (yd^2)/year (0.226 kilogram [kg]/square meter [m^2]/year) (Hay, 1988).

Glacial transport contributes about 0.9 x 10^9 st (0.8 x 10^9 mt) as 0.09 lb/yd^2/year (0.05 kg/m^2/year) and wind transports a total of 1 x 10^9 st (0.9 x 10^9 mt) or 0.8 lb/yd^2/year (0.45 kg/m^2/year). Summary tables in Patrick (1995) show that annual sediment discharge from major rivers in the United States alone exceeds 665 million st (603 Mt) or about 270 st/square mile (mi^2) (94.6 mt/square kilometer [km^2]) (Patrick, 1995). Worldwide values exceed a total of 8.8 billion st (8 billion metric tons [Gt]) or 573 st/m^2 (520 mt/m^2). Other estimates (i.e., Hay, 1988) are much higher, but all studies indicate that sediment is generated and transported in of more than a billion tons amounts each year. Some of this sediment is separated by geologic processes to form minable sand deposits.

Hundreds of millions of tons of sediments including sand-size materials move from high areas to the sea each year as seen in table 5. The Mississippi River alone carries between 280 and 300+ million st (254 and 272+ Mt) of sediment each year (Ritter, 1986). Holeman estimates 5.5 x 10^9 st (5 x 10^9 mt) of sediment are generated per year (Holeman, 1981). Local transport depends on climate, rock types, relief, and land uses. Drainage areas that have rapid weathering, high topographic relief, weak rocks, and little vegetative cover produce the most sediments. Regions that have undergone glaciation are also prolific producers. Even a small, low-gradient stream can transport hundreds of tons of sand in a single flood (fig. 14).

Table 5. Suspended-load denudation in basins of different size in the United States modified from Ritter, 1986.

Basin	**Location**	**Area (mi^2)**	**Average Annual Suspended Load (tons x 10^3)**
Mississippi	Louisiana	1,243,500	305,000
Colorado	Arizona	137,800	149,000
Columbia	Washington	102,600	10,300
Rio Grande	New Mexico	26,770	9,420
Sacramento	California	27,500	2,580
Alabama	Alabama	22,000	2,130
Delaware	New Jersey	6,780	998
Yadkin	North Carolina	2,280	808
Eel	California	3,113	18,200
Rio Hondo	New Mexico	947	545
Green	Washington	230	71
Alameda	California	633	221
Scantic	Connecticut	98	7
Napa	California	81	63

Figure 14. Many tons of sand were deposited in this forest during one flood event on a small, low-gradient stream in the Midwest.

Sediment transport can even renew mined areas in streams as noted by the California Assessors' Handbook:

> Some commercial aggregate deposits are located in or close to existing stream channels. As a result, there are no stable physical reserves. The movement of water may bring in or remove material with changing seasonal water levels. Keeping track of the reserves in such a situation is difficult not only for the operator, but for the appraiser as well. Instead, most operators of such properties know from experience that the reserves will ultimately be replenished, although there have certainly been cases of long years of drought where that has not been the case. Accordingly, it is the Board's position that such properties receive a base year value, in conformance with procedures established for other mining properties with the following exceptions:
>
> - No allowance shall be made for depletion
> - No new reserves shall be added unless the property is expanded in size or some other mining method is utilized.
>
> Obviously, if new material is typically brought into the site naturally, the typical depletion does not occur. Therefore, no allowance for depletion should be made. (California State Board of Equalization 1997, chap. 6)

Miners have known that certain riverine sand deposits replenish themselves by trapping some moving sediments in mined pits. Langer noted that aggregates can be skimmed off sand bars when subsequent high river-flows can replenish deposits (Langer, 2003, p. 14). Mining in river systems can cause adjustments in channels but careful mining can actually stabilize channels if extraction does not exceed sediment influx (Sandecki, 1989, p. 93). Removal of gravel from the Fraser River was thought to have lessened aggradation therefore; reducing flood potential (Church, 1999, p. 17). Many other reports of sand replenishment in rivers are known, and the unceasing action of running water carrying sediments assures abundant sand deposits.

Activities by humans affect sediment transport. Construction of dams decrease sediment delivery (Kondolf, 1997, p. 533), but other activities such as logging and farming increase sediment transport (Wilkinson, 2005, p. 163).

Many estimates of sediment discharge to the oceans have been made; these were summarized by Holeman (1968) and updated by Millimann and Meade (1983), Ritter (1986), and Meade and others (1990). Worldwide sediment discharge rates range from 14.9 to 20.2 billion st (13.5 to 18.3 Gt) per year. North America alone contributes from 1.7 to 2 billion st (1.5 to 1.8 Gt) each year (table 6). While much of the sediment is fine-grained mud or silt, a substantial amount is made up of sand-size materials. There is even more sediment produced by weathering that is sorted and stored in rivers or lakes along the way. Probably five to ten times the ocean discharge tonnages are stored in rivers. As much as 90 percent of eroded sediments exist along rivers or lakes. Sediments delivered each year to the Great Lakes alone are ten times the total annual industrial sand production (Meade and others, 1990). Clearly much more raw sand is generated annually than is used by man.

Table 6. Annual sediment discharge rates (comparison of rates by Holeman [1981]and Milliman and Meade [1983]) modified from Milliman and Meade, 1983.

Area	**Sediment Discharge (10^6 mt yr^{-1})**	
	Holeman, 1981	**Milliman and Meade, 1983**
North & Central America	1,780	1,462
South America	1,090	1,788
Europe	290	230
Eurasian Arctic	---	84
Asia	14,480	6,349
Africa	490	530
Australia	210	62
Large Pacific islands	---	3,000
Totals	18,300	13,505
Note: Northern Africa, Saudi Arabian peninsula, and western Australia are primarily desert and assumed to have little annual discharge of river sediment. Total land area is 11.40 km^2.		

Publications of the USGS, which monitors mineral production and resources, clearly state that quartz sands are in plentiful supply in the United States and elsewhere. There will be resources for many years even without renewal, but renewal will certainly continue. Sandstone, quartzite, tripoli, chert, and other consolidated sources of quartz are deemed by the USGS to be adequate for many years. Even though deposits do not occur everywhere and some deposits are not available for political or economic reasons, quartz-sand supplies should be readily available for centuries.

As we have seen, quartz mineral grains formed along with other minerals in igneous rocks are liberated by weathering processes. During transportation toward the sea, quartz is reduced in size and separated from other minerals into various deposits by geologic agents of gravity, water movement, air currents, longshore drift, and waves. In rivers, beaches, offshore islands, shoals, and sand dunes, sand is replenished via sediment transport after or even during mining. Huge volumes of sand and other sediments are constantly in motion. Previous discussions provide some idea of the amounts. The 30+ million st (28+ Mt) of silica sand mined each year could easily be replaced many times over by normal geologic processes.

SUMMARY AND CONCLUSIONS

- Quartz is one of the most abundant minerals and is made of the most common chemical elements on earth.

- Geologic processes continuously form, liberate, transport, sort, clean, and concentrate huge amounts of quartz.
- Quartz sands are raw materials for the vital construction, chemical, and glass industries.
- Millions of tons of quartz sand are mined each year.
- Quartz sands are very abundant and widespread. Known deposits could last for hundreds of years.
- New deposits of sand are generated in the hundreds of millions of tons each year by normal, ongoing geologic processes.
- Low-grade deposits can be upgraded by well-known beneficiation processes.

The Earth undergoes constant changes. Certain igneous processes form the abundant mineral quartz, which is very stable both chemically and physically. Weathering and transport liberates quartz and other minerals from preexisting rocks, reduces the sizes of grains, modifies grain shape, sorts grains by size, and reduces contaminating materials to form economic deposits of pure quartz sands known as industrial sands. Quartz in various forms is used in large quantities (millions of tons) for construction, glass, fiberglass, and in lesser amounts for many products or processes.

The United States used about 30 million st (28 Mt) of industrial sand in 2004, (1.9 million st [1.7 Mt] is fiberglass alone), and worldwide consumption exceeded 126 million st (115 Mt). Enormous amounts of quartz sand are generated and so the resource is renewed. Some deposits renew themselves annually or almost annually because of floods, storms, or other acts of nature that move large volumes of sand. Others may require many years. The good news is that abundant resources of industrial sand exist in the United States and worldwide, enough to satisfy human needs for hundreds of years. In addition to these existing resources, new or renewed deposits of sand are continuously being produced.

Silica sand is one of man’s oldest, most important, and most abundant raw materials. It has served us well and shows no signs of running out. Indeed some geologic situations replenish sand deposits, making it one of the few renewable or even rapidly renewable geologic resources. The time of sands, as the early geologist James Hutton might say, shows no vestige of a beginning, nor any prospect of an end.

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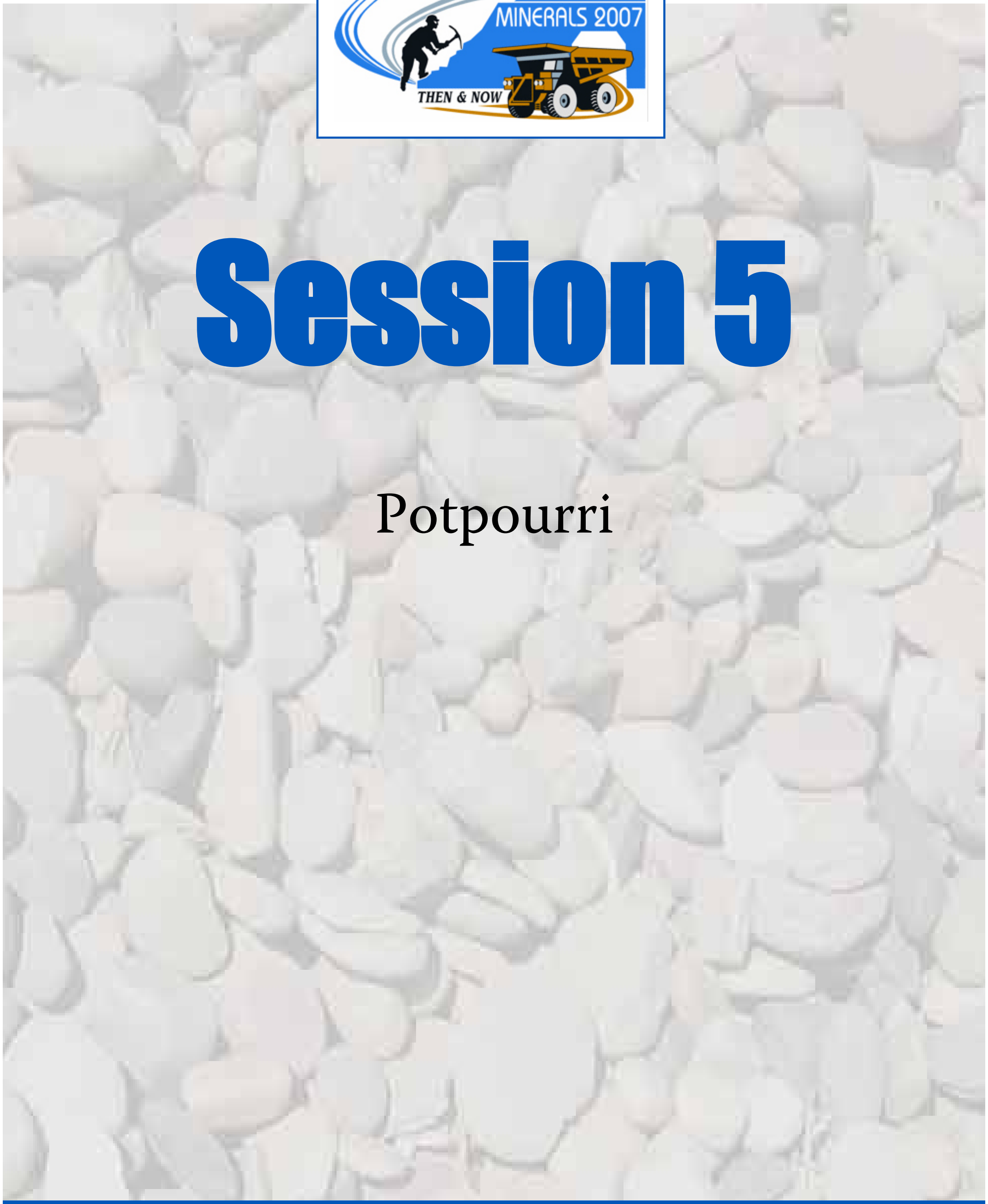

Session 5

Potpourri

Coal Combustion Products as Recovered Industrial Mineral Resources

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ABSTRACT

The U.S. electric utility industry burns more than a billion tons of coal annually, producing in excess of 123 million tons of coal ash and air emission control residues. Though these materials have been historically considered wastes, this perception is changing.

Fly ash, boiler slag, bottom ash and flue gas desulfurization (FGD) material are collectively referred to as coal combustion products or “CCPs.” Their “product” status has evolved with proven commercial and environmental benefits. CCPs offer equal or superior performance over commonly accepted materials/products. CCPs may be used to produce portland cement and can serve as fillers in asphalt concrete paving and in paints, metals castings and other specialty processes. For example, substituting fly ash for portland cement reduces landfill space and disposal costs. Also, every ton of fly ash used instead of portland cement, saves the environment from one ton of CO2. CCPs have proven invaluable in numerous geotechnical and land applications to reduce costs and lower construction’s impact on the environment. Nearly 30 percent of the gypsum panel products produced in the U.S. is manufactured from power plant FGD gypsum. A number of CCPs are used in agricultural and agronomic processes to improve soils and increase crop productivity.

This paper provides an overview of the CCP industry and the materials it produces, and discusses a variety of CCP applications. It addresses some federal and state regulatory opportunities and challenges which impact management and use. Finally, it briefly describes research and testing underway to minimize the impact of air emission control, which may be detrimental to fly ash use.

Partnerships among the CCP industry, academia, federal and state agencies, and the general public help increase awareness of how CCPs can have a positive environmental and economic impact on communities. Demonstration projects and outreach supported by the EPA, the Department of Energy (DOE) the Department of Agriculture (USDA) and the Federal Highway Administration (FHWA) have encouraged many CCPs to become widely accepted.

The large volume of CCPs and other industrial byproducts produced annually represents a tremendous opportunity for the U.S. to greatly increase its sustainable and green practices. Reducing an industry’s carbon footprint by increasing the use of recovered mineral resources pays environmental, economic and social dividends, while still maintaining the required quality of engineering and construction standards.

COAL COMBUSTION PRODUCTS (CCP) BASICS

More than half of the electricity generated in the United States comes from coal-fueled power plants. As part of the electric generation process, coal ash and other residues are created as industrial byproducts. Collectively, these residues, such as fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) materials are known as coal combustion products or “CCPs.” Because many of these CCPs have legitimate commercial use and can be incorporated in construction and manufacturing activities without extensive processing the name “products” is applied. In 2005, overall utilization of fly ash, bottom ash, boiler slag, flue gas desulfurization materials and fluidized bed combustion ash was a little more than 40 percent. Of the approximately 123 million tons produced, slightly more than 49 million tons were used in a variety of beneficial applications (American Coal Ash Association, 2006a).

Concrete production continues to be the largest single application of fly ash in the U.S. In 2005, almost 15 million tons were used as a replacement for portland cement in concrete, concrete products or grouts (American Coal Ash Association, 2006a). While this may seem a “mature” technology, research continues finding better uses for fly ash as a supplementary cementitous material. The impact of residual carbon from the combustion and emission control processes can prevent ash use in concrete. Several new technologies have emerged to help address this issue. “Beneficiating” the ash by processing it in some manner to remove the carbon is gaining wider acceptance. A number of utilities have found that investing or partnering in technologies to remove carbon has resulted in increased sales of fly ash while eliminating need for disposal.

For many years, boiler slag has held the position as the CCP with the highest utilization rate. Applied as blasting grit, in roofing applications or in snow and ice control, it is not uncommon to see ninety percent or more of the boiler slag being used beneficially. Slag is produced predominantly in cyclone or slag tap boilers. As these older style boilers are retired, the amount of slag produced by electric utilities will decrease.

The CCP category that will increase at the fastest rate in the next few years is flue gas desulfurization (FGD) material. Varying types of air emission systems are installed on power plants to remove sulfur and nitrogen oxides. An FGD system typically uses limestone or lime to capture sulfur. Depending on the design of the system, “FGD gypsum” or “synthetic” gypsum may be produced. It is anticipated that FGD gypsum will double in production within the next decade. The dramatic increase in production will come from many utilities that will add FGD emission control systems to their plants to achieve compliance with the Clear Air Interstate Rule (CAIR) and/or the Clean Air Mercury Rule (CAMR). Nearly 12 million tons of FGD gypsum were produced in 2005. Of that amount, more than 8 million tons were used in the production of gypsum panel products (American Coal Ash Association, 2006a).

FGD gypsum has many potential benefits for use in agricultural applications. More soluble than natural gypsum, FGD gypsum can improve plant growth, reduce the need for water in many crops, add micro-nutrients to fields and decrease the amount of runoff in some soil conditions. FGD gypsum is also used in portland cement production and land reclamation activities. There are other types of flue gas desulfurization byproducts besides FGD gypsum, but these have much more limited applications and the markets for their end-uses are growing very slowly.

When fly ash cannot be used as an admixture in concrete, or as an enhancement to portland cement it may be used in other ways. For example, fly ash and bottom ash can be used as raw feed stock in the manufacture of portland cement. Minerals such as iron, aluminum and silica contained in these ashes can replace natural materials that might have to be extracted from pits or quarries. When these opportunities are not available, the ash can be used in structural fills or land reclamation projects, such as on mine sites. Blending CCPs with natural materials can provide technically equivalent mixes as compared to conventional materials. Properly designed structural fills or reclamation activities will have no negative impact on the environment and may help reduce the costs of the project and eliminate need for disposal in landfills.

CCPs can also be used in soil stabilization or modification, as mineral fillers, in mining uses, as aggregates, in agriculture and as ingredients in controlled low strength materials. The types of CCPs, the market factors such as transportation and competing materials and state regulatory guidance may all have an impact on the ability of a material to be used beneficially. The last and least desirable option is disposal.

The challenges facing CCP producers are many, but are continually and constructively being addressed. The following issues affect CCP utilization:

- Design of a power plant boiler;
- Type of coal or fuel used;
- Air emission control devices installed (if any);
- Distance to the marketplace;
- Cost of disposal;
- Availability of land for disposal; and
- Regulatory inconsistencies and changes.

THE CHALLENGE OF REGULATORY REQUIREMENTS

Utilities are constantly under government and public scrutiny for their actual or perceived compliance with environmental regulations. FGD scrubbing systems installed to remove nitrogen oxides (NOx) and sulfur oxides (SOx) are continually impacting plant operations, including those related to ash management. For example, plants that have traditionally produced and marketed high quality fly ash used in concrete are now contemplating the addition of new air emission control systems to comply with CAIR and CAMR requirements. These changes may render the ash unsuitable (e.g., higher unburned carbon content) for their long-established markets. As a result, some companies will elect to install ash beneficiation systems to permit continued sales for their fly ash. These systems process the ash by burning out the carbon or separating electrostatically. The remaining fly ash is of a high quality and the secondary carbon streams can be used as fuel or in other manufacturing processes.

Another possible way to comply with new emission regulations is fuel switching or fuel blending.

If a utility is able to purchase millions of tons of coal at a lower price than established contracts, that is a significant economic incentive. The cost savings for such a decision can be enormous. When alternative coal sources are used, power plants may make changes that impact CCP chemical content and previously developed applications and markets.

Because of these changing coal sources, the availability of Class “F” ash (which comes from bituminous coal) has been significantly reduced in some areas. Additionally, another challenge has been the introduction of Class “C” ash (that produced by burning sub bituminous coal) into areas where they have never been used before. It is not a simple matter to substitute one type of coal ash for another without testing and evaluations of field performance. As mentioned above, another impact of fuel blending has been the reduction of concrete quality fly ash available to the marketplace. Previous and current state approved sources of fly ash may also need to be re-evaluated based on the use of the new or blended fuels.

The EPA implemented the CAMR (the Clean Air Mercury Rule) in 2005, which requires most U.S. utilities to add mercury capture systems to their existing power plants (Federal Register, 2005). Annually, U.S. utilities release approximately 45 tons of mercury into the environment. This represents roughly 35 percent of the total man made mercury emitted in the United States and 1 percent of the global mercury production. Asia emits roughly half of the 2400 tons of man-made mercury produced each year. Implementation of CAMR will be determined by plant owners over the course of the next several years, with full compliance required by 2018. However, some states are evaluating the concept of more stringent regulations that could have a significant impact of the utilities in those affected states well in advance of 2018.

Depending on where in the plant the mercury capture technology is installed, fly ash characteristics may be affected. If installed after the ash collection system, there should be no impact on ash marketing. If it is placed before the precipitator or bag house, the fly ash may be impacted by additives or sorbents used to remove mercury. Some technologies introduce particles such as activated carbon, silicates or other powdered materials. These additives will become part of the ash stream and may be detrimental to ash quality. Preliminary testing indicates that the amount of mercury that may be taken up by the ash will not require its classification as a hazardous or toxic material. The challenge to utilities and the industry is to meet the new environmental standards and still be viable from a business viewpoint.

In December 2006, another aspect of mercury in beneficial use was identified. Similar to regulations for the U.S. utility industry, the EPA has promulgated mercury regulations that will apply to cement kilns involved in portland cement production. The EPA noted in its rulemaking that it had recently become aware of a concern about using fly ash as a raw feed for some cement kilns. As a result, the EPA has banned the use of fly ash as a raw feed when the fly ash mercury content has been increased through the use of activated carbon or any other absorbent unless the kiln can demonstrate that fly ash use will not result in an increase of mercury emissions over baseline emissions. The EPA logic is simple. If a power plant removes mercury from its flue gases, and that mercury attaches itself to the fly ash, which is subsequently used in cement production, the re-release of the mercury from the kiln negates the collection of that same mercury from the power plant. However, the EPA admits that more than just ash alone contributes to mercury release from cement kilns. Natural materials (such as shale, limestone, clay, etc.) are likely involved (Federal Register, 2006).

OPPORTUNTIES FOR BENEFICAL USE THROUGH PARTNERSHIPS

The challenges identified above are significant. Of particular importance to many companies is how to maintain continued CCP beneficial use (and revenue) while addressing air emission requirements and modifications to plants to achieve compliance. One key to expanding the use of CCPs is the wide dissemination of accurate beneficial use information. Joint industry and government information exchange partnerships can have a positive impact. Likewise, research and the distribution of research data can help remove barriers through increased understanding of the performance of CCPs. Collaborative relationships with organizations that have allied interests can also help make information available to potential end users and specifiers.

In 2003, the EPA initiated the Coal Combustion Products Partnership, or "C^2P^2". Sponsored by the EPA, DOE, FHWA, USDA, ACAA and the Utility Solid Waste Activities Group (USWAG) this program is intended to help make people aware of the environmental, technical and economic benefits of using coal ash in a variety of ways. The Agency recognized that in many situations, CCPs could be used to further national environmental goals such as the reduction of greenhouse gases, conservation of natural resources and lessening the need for coal ash landfill space. The program is aimed at identifying the actual or perceived barriers that limit the beneficial use of CCPs in highway and construction applications. Some of these barriers exist because there is a lack of understanding by end users and government agencies of the potential benefits of CCPs. These efforts are anticipated to increase CCP use. The EPA's C^2P^2 website (http://www.epa.gov/c2p2/) provides a number of case studies. There are no costs to join nor are there any specific goals, other than a shared interest in increasing ash utilization. At the time of this writing, approximately 150 organizations have joined C^2P^2.

Another partnership that is evolving on a regional basis is the Green Highways Partnership (www.greenhighways.org). EPA Region 3 and the FHWA office in Philadelphia jointly recognized an opportunity in early 2005 to create a context sensitive approach to environmental planning as part of highway construction activities. The construction or reconstruction of roadways, bridges, and other transportation infrastructures can have a major impact on local land uses. Region 3 started dialogue with planners, designers, state and local transportation officials, contractors, industry associations and others to find a better way of addressing environmental concerns. As the result of a number of meetings and a collaborative conference held in College Park, Maryland, the Green Highways Partnership (GHP) was formed. Through concepts such as **integrated planning**, **regulatory flexibility**, and **market-based rewards**, GHP seeks to incorporate **environmental streamlining and stewardship** into all aspects of the highway lifecycle.

There are three focus areas for GHP – watershed driven stormwater management, conservation and ecosystem protection, and reuse and recycling. The ash industry and their partners in the Industrial Resources Council are particularly focused in this latter arena. By helping planners, designers, owners and contractors realize that many industrial byproducts can be used as effectively and often times cheaper than virgin materials, it is anticipated new markets will be developed for CCPs and similar residues. Because many CCPs meet the technical and quality requirements of natural products, the goal of the GHP is to encourage the use of these materials in lieu of natural materials thus conserving resources and eliminating need for landfill space. It is anticipated that the GHP concept will become a national program within several years, giving America more sustainable highways and transportation systems.

In 2002, the EPA hosted the first national summit on the beneficial use of industrial byproducts. Those in attendance included producers of non-hazardous wastes and state agencies responsible for reviewing and approving these materials' beneficial use. This permitted open and valuable dialog for sharing experiences in land applications. In some cases, partnerships were formed to further investigate potential for beneficial use of many materials. Attendance has increased from 70 in 2002 to more than 250 participants in 2006. The next summit will be held in Denver in the spring of 2008.

In addition to national summits, EPA's ten regional offices are tasked by the Office of Solid Waste in Washington, DC to become more involved in the use, reuse and recycling of industrial materials. In 2006, CCPs and foundry sands were two focus materials (referred to as "secondary" materials by the EPA) of the regions. The ACAA and several industry associations were closely involved in planning one-day workshops in Dallas, Milwaukee, Buffalo and New York City. As each EPA region becomes more aware of the technical and environmental benefits of using CCPs, the marketplace for these materials will likewise increase.

In late 2006, the USDA became a C^2P^2 sponsor. The USDA, primarily through its Agricultural Research Service (ARS), has conducted much research and has promoted demonstration projects on the use of CCPs in agribusiness. The ARS has a number of research stations that, in conjunction with land grant universities, have demonstrated and analyzed the impact of using CCPs, such as FGD gypsum in land applications. This material can add micronutrients to certain crops to increase yields and it can also ameliorate sodic soils and be successfully used in no-till or tilled crops. With anticipated growth of FGD gypsum in the next ten years, this type of research could open many doors to increased usage.

Forming partnerships can be one of the most effective ways to induce new technology or promote specific applications. Numerous examples exist demonstrating where long term community and economic benefits are derived from local partnerships with public agencies, CCP producers and marketers. Involvement of the EPA, DOE, USDA and FHWA with local and state government officials promotes understanding that CCP use can be environmentally sound and still meet the required performance and design needs for construction projects. Regional CCP partnerships such as the Midwest Coal Ash Association, the Texas Coal Ash Utilization Group and the Western Region Ash Group have been created where special issues unique or important to a geographic location can be addressed.

Industrial partnerships have also been formed where industries share a common awareness of the need to reuse and recycle residual industrial materials. Many cement producers include fly ash and other CCPs in their menu of products in order to further the overall use of concrete in construction. The “green” movement in the United States and evolution of the U.S. Green Building Council and the Green Building Initiative known as “Green Globes” has resulted in broader support of many industries to provide more environmentally sensitive projects. The ash industry is involved in associations that promote concrete use, including the Environmental Council of Concrete Organizations (ECCO), American Concrete Institute (ACI), American Concrete Paving Association (ACPA), Portland Cement Association (PCA) and National Ready Mix Concrete Association (NRMCA), to name a few.

A relatively recent partnership is the Industrial Resources Council (IRC). Recognizing the similarity of issues faced by byproduct industries, ACAA began discussions with a number of associations, including Foundry Industry Recycling Starts Today (FIRST), Construction Materials Recycling Association (CMRA), the National Council for Air and Stream Improvement (NCASI), which represents the wood and paper products industry, the Rubber Manufacturers Association (RMA), and the National Slag Association (NSA) and Slag Cement Association (SCA). All these organizations are industry groups that see the beneficial use of their materials as sound environmental, economic and technical alternatives. It was natural, that their common interests gave rise to the idea of forming a partnership to address common opportunities and barriers. The IRC is envisioned a clearing house for information pertaining to the beneficial use of coal ash, foundry sands, wood and paper industry byproducts, slag for the iron and steel industry, selected construction and demolition debris and scrap tires.

The EPA favors the formation of partnerships like the IRC as they enable the agency to better use its own resources. Instead of many similar programs for beneficial use of five or six or more byproducts, the Agency can work with the IRC instead. Funding opportunities may exist for the IRC from the EPA to support outreach and education related to a variety of industrial materials. Although the IRC is an entirely voluntary effort by the associations identified above, the concept of this partnership has significance. It is one of the first examples of diverse industries with competing products forming an alliance to address issues of common interest.

Members of the IRC are still dedicated to their own products, but they also look for projects to combine their materials with those produced by other IRC members in order to convince specifiers and end users of the value of use and reuse of the materials. In many ways, these relationships fit very nicely with the goals of the Green Highways Partnership described above.

In 2005, Congress passed the Energy Policy Act (EPACT) and the Safe Accountable Flexible Efficient Transportation Equity Act: A Legacy for Users (SAFETEA LU). Part of the language of these bills is to conduct a study and prepare a Report to Congress within 30 months on several elements of the two bills. One is a renewed effort to encourage using concrete in projects using federal funding. The second is support of using "recovered mineral components" such as coal combustion fly ash (in addition to ground granulated blast furnace slag, and other "waste materials or byproducts" diverted from the solid waste stream) (American Coal Ash Association, 2006b). These two bills have the potential to significantly influence procurement officials and specifiers to look more closely at the use of concrete and to call for supplementary cementitous materials in the concrete. SAFETEA LU also opens the doors for CCP use in ways other than just concrete mixes.

CONCLUSIONS

The United States CCP industry is in a constant state of change. CCP use is growing and new applications are being found for a variety of materials. At the same time, there are current and future challenges for producers and end-users. Environmental pressures make land filling a less desirable alternative than beneficial reuse. The development of partnerships with regulators, universities, producers, marketers and end-users helps create new markets. Developing technically sound methods of using CCPs in such a changing environment may require the collective agreement of many parties. Regulatory agencies must be assured that the end-use will not create new problems.

Even though the specific cases may differ in location, quantities and end uses, properly managed applications using CCPs will achieve desired physical, environmental, economic and social results. Forming partnerships with other industries and government entities creates many opportunities for increasing markets and identifying new uses for CCPs and other similar materials. The industry, working together with other stakeholders is continuing to address change and challenges in positive ways. The opportunity to conserve other materials, to recycle what some consider to be an industrial waste and to benefit from cost savings that can be realized in such uses is important to the United States and many other countries in the world.

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Diamond Deposits of the North American Craton

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ABSTRACT

Diamonds have been found in placers in North America derived from unknown sources. Others were recovered from glacial deposits from distant lands. The number of placer diamonds found in North America indicates that several source deposits would be discovered.

Some discoveries initially led to developments of small mines in Murfreesburo, Arkansas (Prairie Creek) and the Colorado-Wyoming State Line district (Kelsey Lake). World-class diamond deposits have eluded the United States to date, but have recently been found in Canada, which has led that nation to becoming a major source of gem-quality diamonds over a very short period of time. Canada now ranks as the third largest diamond producer of gem-quality diamonds in the world, which followed the development of their first mine (Ekati) in 1998 and second mine (Diavik) a few years later. A third mine was recently dedicated (Jericho) and two additional mines are under development – all world-class deposits! With thousands of additional discoveries, other diamond mines will be developed in the future of Canada. The timing of this diamond boom and rush occurred at a promising time, when major diamond mines in Africa, Australia and Russia were showing declining production.

Even though favorable Cratonic (Archon) basement rocks extend south of Canada under large portions of the United States, essentially all meaningful exploration has been confined to Canada over the past 25 years. Reports of hundreds of diamonds along with hundreds of kimberlitic indicator mineral anomalies, kimberlites, lamproites, lamprophyres and some distinct geophysical anomalies in the U.S., would lead one to anticipate that exploration could result in significant discoveries in the U.S. – however, the political climate in the U.S. remains archaic at best for exploration.

The favorable Cratonic terrains in Canada that are host for some very impressive diamondiferous kimberlites does not stop at the Canadian border but continues southward into the Great Lakes region (Superior Province) and into Wyoming and Montana (Wyoming Province). One should anticipate that major swarms of mantle-derived intrusives continue southward into Montana, Wyoming, Colorado, Michigan, Wisconsin, and Montana and that this terrain could potentially become an important source for diamonds in the future – a scenario that is unlikely unless there is modernization of exploration regulations and removal of many bureaucrats in government agencies.

This craton and cratonized margin has been intruded by widespread swarms of these mantle-derived magmas. The North American craton is predicted to become the principal primary source of gem and industrial quality diamonds in the near future and for decades to come.

This paper is dedicated to the memory of three wonderful friends and geologists; John Dooley, Ray Harris and Robert Lyman. It is difficult to lose a friend so early in life, but three in their prime?

INTRODUCTION

There are many deposits of diamond that are found throughout the world: some are the classical kimberlite- and lamproite-hosted deposits; others are placers derived from the erosion of these rocks, and still others are classified as unconventional and include a whole variety of deposits, some of which may someday be found to host commercial amounts of diamonds. Most notably are some lamprophyres. Still, the search for commercial diamond deposits continues to focus on kimberlite and less often on lamproite.

Commercial diamond deposits are extremely rare. In the richest primary mines, diamond is found in concentrations considerably less than 1 ppm (Lampietti and Sutherland, 1978). Most primary diamond deposits are found within thermally stable Archean cratons that have relatively thick cratonic keels (termed Archons) and in cratonized Proterozoic belts accreted to the margins of the Archons (termed Protons), and with the discovery of many unconventional diamondiferous host rocks in recent decades, a new exploration philosophy is necessary, as some of these host rocks have significant numbers of diamond (Hausel, 1996; Erlich and Hausel, 2002). In the past, unconventional host rocks have only been cursory sampled or ignored by exploration groups and little effort is made to evaluate these deposits (Erlich and Hausel, 2002). Even so, significant amounts of diamond can be expected in some unconventional host rocks, in particular, those associated with subduction tectonics (Erlich and Hausel, 2002; O'Neill and Wyman, 2006), where one might expect significant organic carbon in diamond formation, as well as stressed diamonds potentially producing higher percentages of valuable pink diamonds.

The world's natural diamond deposits are mostly mined from a small group of primary and secondary deposits that have operating lives of 10 to 30 years. A notable exception is the South African Premier mine, the source of many of the world's largest gem diamonds including the 3,106 carat Cullinun, the largest ever recovered. The Premier mine operated for more than 100 years. Another exception is the marine placers along the western coast of Africa, which have been productive for decades. Nearly all exploration companies spend their efforts searching for world-class diamond deposits and ignore smaller, yet potentially productive minor deposits, such as those mined at Kelsey Lake, Colorado and Murfreesburo, Arkansas. This archaic philosophy has left the door open to smaller companies to search for small to medium size diamond deposits.

The top natural diamond producers in the world, based on total carats recovered (gems plus industrial stones) are: Botswana, Russia, Canada, Congo, South Africa, Australia and Angola (Hausel, 2006). Notably absent from this list is the U.S., even though large parts of the United States are underlain by a cratonic basement terrain suitable for the discovery of diamond. Canada, which became a major diamond producer in 1998, will remain in the forefront of diamond production and exploration for decades to come. Not only is the Canadian Shield favorable for discovery of significant diamond deposits, but the various Provincial and Territorial governments provide exploration and investment incentives unmatched. There is a perceived negative business climate for exploration in the U.S. that is supported by little to no research funding. As a result, nearly all North American exploration activity and investment for diamonds has focused on Canada. This philosophy has led to the discovery of more than 500 Canadian kimberlites and dozens of unconventional host rocks over the past 2 decades - nearly half of which are diamondiferous (Kjarsgaard and Levinson, 2002). These discoveries are unfortunately restricted to political boundaries and continuation of diamond discoveries to the south of the Canadian border has been almost nonexistent in the past decade due to gothic politics on the state level.

Research

Grassroots exploration for diamond deposits in the United States is almost unheard of. This is the result of an archaic system of exploration regulations and laws that favor a plethora of government agencies. The North American Craton is represented by a very old continental core that provides a favorable geological environment for the discovery of diamonds. The North American craton is also the largest craton in the world with vast regions available for diamond exploration (fig. 1). This cratonic basement projects south from Canada into the Wyoming Province and the Superior Province. The older (greater than 2.5 Ga) regions of the craton (known as Archons) have the highest potential for discovery of commercial diamond deposits associated with kimberlite. The more favorable terrains for diamond exploration in the U.S. extend under Montana, South and North Dakota, Colorado and Wyoming as well as into the Great Lakes region of Michigan, Wisconsin and Minnesota. Even with these favorable protrusions of cratonic basement into the U.S., the political climate has been less than favorable south of the border. As an example, investment in exploration and research in Wyoming Province – the most favorable extension of the North American craton in the U.S., amounted to considerably less than 0.01 percent of investments in Canada over the past decade.

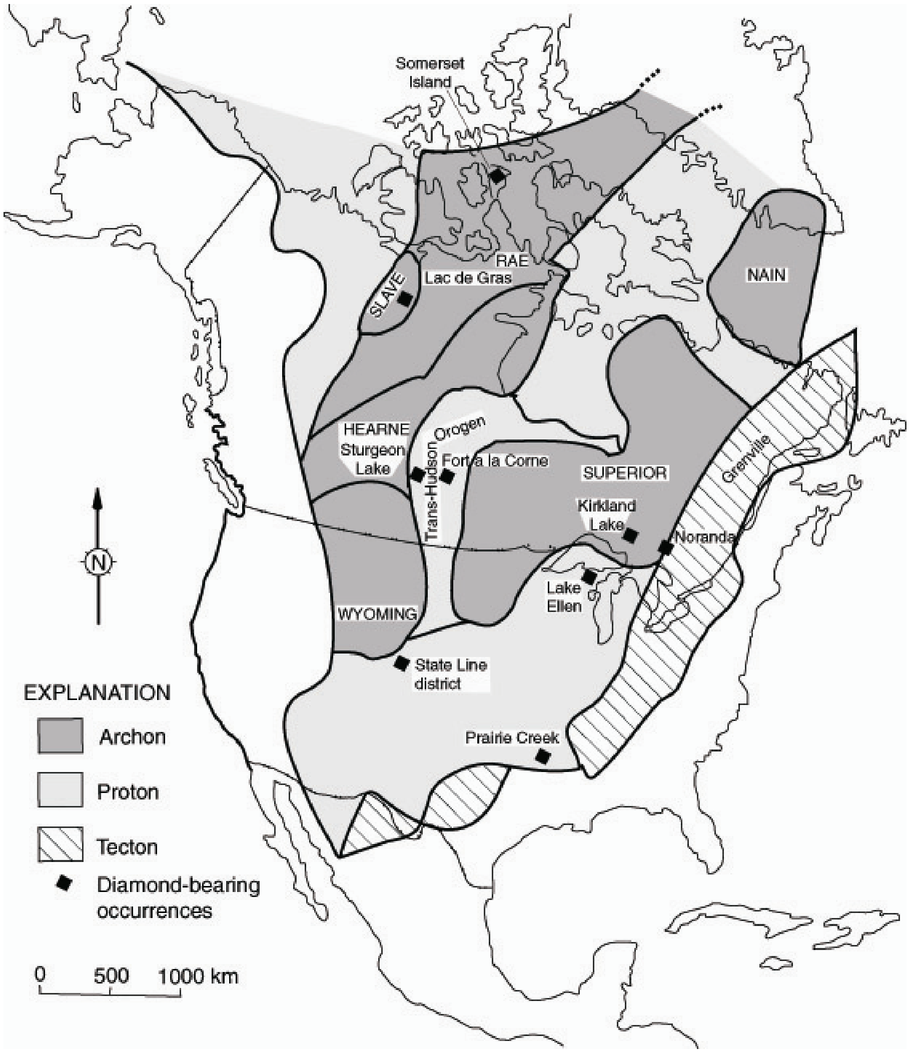

Figure 1. The North American craton. The older cratonic cores, referred to as Archons (greater than 2.5 Ga), have the highest potential for discovery of conventional diamondiferous host rocks. The Proterozoic basement terrains (2.5 Ga to 1.6 Ga) referred to as Protons, are thought to have moderate potential, and Tectons (1.6 Ga to 0.6 Ga) have low potential (after Janse, 1994).

A comparison of the research expenditures invested by the State of Wyoming (about $100,000) over the past 10 years to the exploration and research investments of Alberta (more than $70 million) and the Northwest Territories (more than $2.0 billion), it should be clear that the State of Wyoming is under-explored.

With little to no support over the past few decades, the Wyoming Geological Survey identified hundreds of anomalies – anyone of which could lead to a major discovery. These included more than 300 kimberlitic indicator mineral anomalies, more than 100 vegetation anomalies typical of those associated with many kimberlites, and geological maps produced of the two largest kimberlite districts in the U.S. and the largest lamproite field in North America (Hausel and others, 1981; 2003; Hausel, 2006).

Many diamond exploration projects in Canada are well funded and significant discoveries have now been made in every province and territory. In contrast, little effort has been made by the government in the United States in the search for diamonds and other gemstones.

South of the Canadian border, detrital diamonds, hundreds of kimberlitic indicator mineral anomalies (KIMs), dozens of vegetation anomalies, circular geomorphic and vegetation anomalies, geophysical anomalies, known kimberlites and the largest field of lamproites in North America have been identified. Many diamonds and diatremes have been discovered throughout various regions of the U.S., both within the cratonic environments and also in unconventional terrains (Hausel, 1996; 1998). Some of the more notable terrains in the U.S. include the Appalachian Uplift, the Arkansas Proton, Superior Province, the Wyoming Craton and the California Sierra Nevada and coastal mountain terrains.

Mineralogy & Geochemistry

Both gem and industrial diamonds have been created in the laboratory (Hazen, 1999), but the value of synthetic gem diamonds falls short of natural gem diamond. And some natural diamonds represent the most valuable commodity on earth based on price per unit weight (Hausel, 2006).

Native carbon occurs as one of three polymorphs: (1) diamond, (2) graphite, and (3) lonsdaleite (Erlich and Hausel, 2002). The physical differences between these are related to the bonds between carbon atoms. The crystalline cell of diamond approximates a cube with sides of 3.56Å. Coordination of carbon atoms in diamond is tetrahedral such that each atom is held to four others by strong covalent bonds that result in the extreme hardness, incompressibility and thermal conductivity associated with diamond.

In its simplest form diamond forms a cube. Even so, cubic habits are uncommon, and when found, diamond cubes are characteristically frosted industrial stones. Many diamond cubes have been found in placer deposits in Brazil, and a significant percentage of the diamonds recovered from the Snap Lake kimberlites in Canada also have cubic habit (Pokhilenko and others, 2003). A more common habit for diamond is that of an octahedron (fig. 2). Partial resorption of the octahedron can result in a rounded (12-sided) dodecahedron with rhombic faces. Many dodecahedrons develop ridges on the rhombic faces to produce a 24-sided crystal known as a trishexahedron. Four-sided tetrahedral diamonds are distorted octahedrons (Bruton, 1979; Orlov, 1976; Shafranovsky, 1964).

A tetrahedron by definition is a four-faced polyhedron in which each face forms a triangle (Bates and Jackson, 1980). Twinning in diamond commonly follows the spinel law to produce a flat triangular macle.

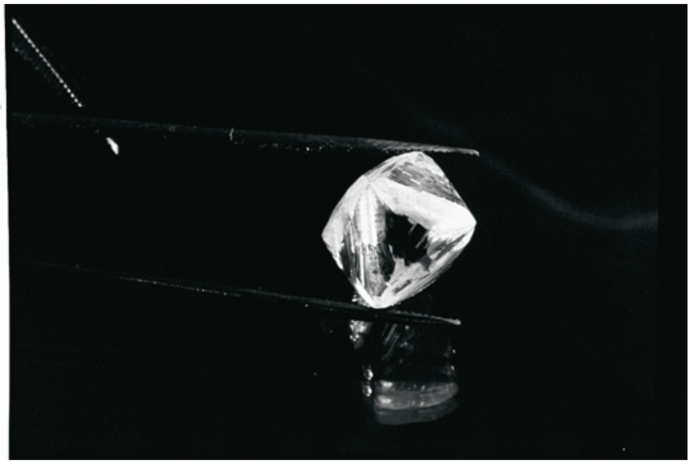

Figure 2. A flawless, 14.2-carat octahedron from the defunct Kelsey Lake diamond mine, Colorado (photo courtesy of Howard Coopersmith).

Diamonds recovered from lamproites often exhibit resorbed habits: octahedrons are typically less common in lamproite than in kimberlite. The many resorbed diamond textures associated with lamproite are a result of diamond instability in relatively hot lamproitic magma as compared to kimberlite. In particular, the slower rate of rise of lamproite magma through the graphite stability field, coupled with high magmatic temperatures in an oxygen-rich environment provides conditions that favor diamond resorption. Similar resorbed habits are found in many diamonds recovered from lamprophyres as well as many kimberlites that exhibit geochemical evidence of eruption as an oxidizing magma. Diamondiferous lamproites also tend to produce a large percentage of industrial to gem diamonds and often many fancy gem diamonds. Some fancy diamonds appear to be associated with deformation in diamond (such as the pink diamonds) and are often found near subduction zones.

Industrial stones may be classified as bort (a poor grade diamond that is used as industrial abrasive) and carbonado (an opaque, black to grayish, fine-grained aggregate of microscopic diamond, graphite, and amorphous carbon with or without accessory minerals) (Erlich and Hausel, 2002). Even though diamond is extremely hard and resistant to compression, it is brittle and will break to yield a conchoidal to hackly fracture along with smooth cleavage surfaces. Diamonds exhibit perfect cleavage in four directions parallel to the octahedral faces: thus an octahedron can be fashioned from an irregular shaped diamond simply by cleaving (Kukharenko, 1954; Orlov, 1977). Natural diamonds contain tiny mineral inclusions along cleavage planes. These provide important data on the origin of diamond and some inclusions can be used for age determinations. The mineral inclusions typically form assemblages that are characteristic of peridotite or eclogite. Some rare inclusions have been identified that are characteristic of very deep mantle sources and interpreted as ultra-high pressure diamonds that originated within the lower mantle (Erlich and Hausel, 2002).

The specific gravity for diamond (3.516 to 3.525) is high enough that it will concentrate in stream, river or marine placers with *"black sand"* heavy minerals. This density is surprisingly high given the fact that diamond is composed of such a light element (carbon). Compared to graphite (2.2), diamond is twice as dense due to the close packing of atoms from high pressures within the earth's mantle (Harlow, 1998). The depth of erosion of many diamondiferous kimberlites in Wyoming and Colorado led Hausel (2004) to conclude that placer diamonds are likely common within and surrounding the Colorado-Wyoming State Line district. Diamonds have been found in black sand concentrates in at least three drainages in the district, even though there has never been any concerted effort to search for placer diamonds. The largest diamond recovered from a drainage in the district was a 6.2 carat stone found in Fish Creek in Wyoming (Howard Coppersmith, personal communication)..

Diamond has greasy to adamantine luster. The luster is distinctive and due to the mineral's high refractive index, this results in a gemstone of unparalleled beauty with extraordinary fire. Diamonds also occur in a variety of colors from white to colorless, gray to black, and shades of yellow, red, pink, orange, green, blue, violet and brown. Strongly colored diamonds are termed fancies and many have extraordinary beauty and sell for premium prices. As an example, in 1989 a 3.14-carat Argyle pink diamond sold for US$1,510,000. More recently, a 0.95-carat fancy purplish-red Argyle diamond sold for nearly US$1 million. Thus, these diamonds are many thousands of times more valuable than an equivalent weight of gold.

The color in most gemstones is due to trace impurities of transition metals. However, the color in diamond is often caused by trace nitrogen, boron or structural defects. Pink diamonds in particular, are thought to result from structural defects. Diamonds may be red, pink, purple, orange, yellow, green, blue, white, black, gray or brown. The most common color is brown. Prior to the development of the Argyle mine in Australia in the 1980s, brown diamonds were considered unattractive and typically classified as industrial stones. But due to Australian marketing strategies, some brown stones are now highly prized gems. Lighter brown diamonds are quite variable and have color tones that range from very light brown, light (champagne) brown, medium brown, dark brown to very dark brown. Color saturation is also variable resulting in bright brown and dark (cognac) brown colors. In particular, champagne and cognac gem diamonds are in high demand due to marketing.

Pink, red and purple diamonds are rare with the colors concentrated in tiny lamellae in an otherwise colorless diamond (Harlow, 1998). The color lamellae are interpreted to be a result of micro-deformation possibly resulting from stresses applied to diamond while crystallizing within an active subduction zone. Areas in North America, such as the Sierra Nevada of California, the State Line district of Colorado-Wyoming, and the Cordillera of British Columbia may be good targets to search for fancy diamonds due to the presence of active a paleo-subduction. At any rate, pure pink diamonds are extremely rare. Most green diamonds have a thin surface coating that is removed during faceting – thus natural faceted green diamonds are rare. The green color results from natural irradiation, while others may result from the presence of hydrogen. The rarest color is orange, for which the coloring agent has yet to be identified in diamond. The range of tones in orange is quite variable in lightness and saturation resulting in pale orange, bright orange, dull orange and deep orange. One of the most exquisite colors for all orange diamonds is a pumpkin orange.

Black diamonds result from the presence of graphite inclusions, which not only color diamond, but also make the diamond an electrical conductor. Individual colors can vary from pale charcoal black, dull ink black, to bright gun metal black, all with weak saturation. Gray diamonds are hydrogen rich and their color is related to light absorption by hydrogen defects. Opalescent or fancy milky white diamonds are the result of numerous mineral inclusions (and possibly nitrogen defects) (Harlow, 1998).

Diamond's high index of refraction (2.4195) is a result of density. High density diminishes light velocity (77,000 mi/sec in diamond) to less than half the velocity of light in a vacuum (Harlow, 1998). Diamonds are four times as thermally conductive (5 to 25 watts/cm/°C) as copper at room temperature. Unlike copper, diamond is also an electrical insulator (0 to 100 ohm/cm at 300°K). Because of its high thermal conductivity, diamond feels cool and the gem will conduct heat away from one's lips, which is why diamonds are sometimes referred to as *"ice"*. Hand-held diamond detectors are designed to measure its unique thermal conductivity. Diamonds are relatively unaffected by heat except at high temperature. Without the presence of oxygen, diamond will transform to graphite residue at 1,900°C. When heated in oxygen, diamond will burn to CO_2 at much lower temperatures (greater than 690°C). Diamonds are unaffected by acids.

Diamonds repel water, are hydrophobic (non-wetable), and attract grease. Even though they are 3.5 times heavier than water, diamonds can be induced to float. Oxygen atoms in water and in a given material tend to link and thus water will adhere to materials that contain oxygen making them wetable, but diamond contains no oxygen. Hydrocarbons such as grease have affinities for material without oxygen. This property is used effectively in grease tables, where tables are coated with grease to attract non-wetable diamonds, while wetable oxygen-bearing minerals tend to wash over grease plates (Erlich and Hausel, 2002).

GEMOLOGY

There are four general types of commercial natural diamonds: (1) *gem* (well-crystallized, transparent, flawless to nearly flawless), (2) *bort*, (3) *ballas* (spherical aggregates formed by many small diamonds), and (4) *carbonado* (opaque, black to gray, tough and compact industrial diamond). Gem diamonds may be further subdivided into *gem* and *near-gem* (lower-quality gemstones).

Rough gem diamonds have values as much as 10 to 100 times greater than industrial diamonds. Gem diamonds, when cut and polished, will fetch values 5- to 100- times that of the rough stone particularly when they are displayed in jewelry. The extreme value of diamond as a gem is due to its mystique, rarity, extreme hardness, preparation, beauty, high refractive index and dispersion that produce brilliant faceted gems with distinctive "*fire"*.

Top cutters in the world produce beautiful gems from rough material and may require considerable pragmatic crystallographic research to determine location of cleavage, fractures, pits, curves, protrusions, inclusions, and color inconsistencies. Some of the more valuable diamonds have been studied and mapped by cutters as much as a year prior to faceting. Since 1981, lasers, and since 1988, computer modeling and scanning, have become an integral part of diamond fashioning. A rough diamond can now be modeled with a computer and scanner to determine the optimum faceted stone using virtual 3D models to display positions of mineral inclusions and virtual saw planes.

The size and shape of rough diamond, the number and location of imperfections and inclusions, and the direction of cleavage (referred to as "grain" by cutters) are considered prior to creating a gem. In the past, many large diamonds were pre-shaped by cleaving. The cutter selected the octahedral cleavage by cutting a small groove in the octahedral plane with a sharp-edged diamond chip, and a steel knife was placed in the groove and struck to create enough force to cleave the stone (laser kerfing may now be used to mark a notch that is burned into the stone).

If the cleavage was improperly identified, the diamond shattered into pieces. Conventional primary shaping is done by cutting the stone with a diamond saw. In the past, diamond is either cut parallel to the cube or to the dodecahedron with a rapidly rotating blade impregnated with diamond powder. Because of hardness, it took 4 to 8 hours to complete a cut through a 1-carat diamond of only 6 to 8 mm in diameter (Hurlbut and Switzer, 1979)! With the use of lasers, this process requires less time. With the desired cut preprogrammed in a computer, a platform moves the diamond through the laser. At the point where the beam is focused, the temperature is extremely high and the molecular structure of diamond is converted to graphite on the first pass. The graphite is then "burned off" on the return pass. Diamond combustion occurs at 690°C to 875°C. Representative cutting time using a laser would be approximately eight hours for a 10-carat crystal (Baker, 1981).

Faceting is completed by grinding and polishing the diamond on a revolving horizontal lap impregnated with diamond powder. In a standard, round, brilliant diamond, as many as 58 facets are cut and polished. The optimum directions for conventional polishing are parallel to the crystallographic axes. Because the cubic faces of the diamond are parallel to axes, they are easiest to polish. Those that lie nearly parallel to an optic axis are more favorable to polish because of lower hardness.

The octahedral face is the hardest on a diamond and lies at the greatest angle from the crystallographic axis. If the plane of the cut or facet varies more than a few degrees from a cubic face, it is nearly impossible to saw. In this case, a laser is necessary to produce cuts and facets. Tiny inclusions of diamond may be scattered within a host diamond. With conventional methods, the diamond inclusions must be avoided during sawing since vibrations produced when a blade contacts the included diamond can cause the host to shatter. If the stone does not shatter, the cutting time may increase 2 to 3 times and extend cutting many days or even weeks. With laser technology, this problem is resolved and may take only a matter of hours. A laser also includes the ability to produce new fancy shapes that were not formerly possible, such as horse-heads, oil wells, stars, butterflies, initials, etc. Many diamonds with distorted growth, such as twinning, were virtually impossible to cut by conventional means because of cleavage changes. However, these stones can now be cut by laser without regard to grain (Baker, 1981).

The finished gem is judged by "*four Cs*"—cut, clarity, carat weight and color. The cut of a diamond can increase its value enormously - the better proportioned, polished and faceted, the greater the value of the finished stone. With diamonds of similar quality, those of greater size can dramatically increase in value with increased carat weight. When the girdle (base) and table of the diamond are correctly proportioned, the diamond will exhibit greater fire and brilliance. Gem diamonds include fancy (colored) and white (colorless) stones. Colorless diamonds range from colorless (white) and blue-white to pale yellow (Bruton, 1978). One of the more common systems for evaluating diamonds is that of the Gemological Institute of America's (GIA) color grading system which ranges from D (colorless) to X (light yellow). Each letter of the alphabet from D to X shows a slight increase in yellow tinge (Hurlbut and Switzer, 1979).

A visual appraisal is done in a well-lighted room using natural north window light. Appraisals compare the stone to a master set of instrument-graded diamonds. The instrument used in color grading is a colorimeter, which quantitatively measures the degree of yellowness (Hurlbut and Switzer, 1979). Clarity is determined by the presence or absence of blemishes, flaws and inclusions. Many grading systems in use have descriptive terms such as flawless (F) or imperfect (I) and terms that denote intermediate grades such as very slightly imperfect (VSI).

Economic Value

Diamond deposits can provide significant economic boosts to local economy and even national economies. Many diamond mines host from $500 million to $75 billion in raw stones. Rough gem diamonds may be valued at only $50 to as much as $400 per carat. Faceted stones are typically valued at 10 to as much as 100 times the raw stone depending on the placement of the stone in jewelry. Diamond mines typically have lives of a decade to 100 years.

The recent discoveries of commercial deposits in and near the arctic north in Canada have resulted in dramatic costs for capitalization of mines. Additionally, spring and summer thaw of the ice roads for mine supplies result in increases in cost of mining, as much of the materials and fuel for the mines have to be flown in at a very high cost. The discovery of commercial diamond deposits further south in Alberta, Montana and Wyoming could provide more favorable capitalization start-ups due to the presence of more favorable infrastructure.

GEOLOGY

Commercial amounts of diamond have only been found in rare magmatic rocks (kimberlite and lamproite) and in placers presumably derived from these igneous rocks. Even so, diamonds have been identified in other igneous rock types (i.e., alkali basalts, lamprophyres, ultramafics, etc) and in some ultra-high pressure metamorphic rocks (Hausel 1996; Erlich and Hausel, 2002). Primary commercial diamond deposits so far have been restricted to ancient stabilized cratons and cratonized margins that include Archons (cratons of Archean age) and Protons (cratonized belts of Early to Middle Proterozoic age). Nearly all modern exploration ventures focus on a search for diamondiferous kimberlite in cratonic terrains.

Primary magmatic diamond deposits are limited to a few rock types that originally formed under extreme pressure and temperature at great depth beneath the lithosphere. The most notable magmatic diamond deposits are associated with kimberlite, lamproite and some lamprophyres. Many diamondiferous kimberlites, lamproites and lamprophyres tend to occur in small or large clusters of a few to more than 100. The clusters can be related to distinct structural control. As a result, more than one intrusive is often found along the same fracture or orientation, or along parallel or cross fractures. Several favorable structural orientations are typically recognized within a given district and most individual structures responsible for the control of the diamond deposits typically have very limited strike lengths. Larger, more distinct structures may occur near some districts and may in some way be related to kimberlite emplacement or a more regional scale (Hausel and others, 1979).

Detailed mapping of smaller linear structures responsible for orientation of kimberlites may lead to discovery of additional hidden to poorly exposed kimberlite (Hausel and others, 1979; 1981; 2000). The emplacement of kimberlite in the Iron Mountain district of Wyoming is thought to have an association with the nearby Cheyenne Belt suture zone (Hausel and others, 2003). This suture is interpreted to represent a paleo-Benioff zone marking the break between the Wyoming (greater than 2.5 Ga) Province to the north, from the Colorado (1.8 to 1.6 Ga) Province to the south (R.S. Houston, personal communication, 1996). The suture lies 6 mi (10 km) north of the known kimberlites at Iron Mountain while the Iron Mountain kimberlites tend to occur along fractures that parallel the projected suture. However, 60 miles further south, kimberlites of the State Line district show primarily north-northwesterly trends with some east-west cross-trends but no evidence of control by major structures (Hausel and others, 1981).

Kimberlite magmas tend to erupt as diatremes (pipes) at the earth’s surface. These erupt with considerable latent energy ejecting pyroclastic material into the air (referred to as crater-facies kimberlite) and disrupting and incorporating blocks of country rock to produce a volcaniclastic rock (fig. 3). The resulting breccia, referred to as diatreme-facies kimberlite, exhibits fragments of kimberlite along with crustal xenoliths and cognate mantle nodules within a serpentinized peridotite matrix. Kimberlite diatremes typically exhibit more than one episode of magma intrusion and often suggest several episodes of intrusion within the same pipe as well as within the same district. For instance six different kimberlite facies were mapped within the Sloan 1 and 2 kimberlite complex in Colorado (McCallum and Mabarak, 1976).

Diatremes are vertical pipes that taper at depth to steeply incline cylindrical bodies that grade into a root zone and dike complex. The average angle of wall inclination at the Wesselton, DeBeers, Kimberley and Dutoitspan pipes in South Africa is 82° to 85°. Ideally, such pipes form circular or ellipsoidal cross sections in the horizontal plane filled with kimberlitic tuff or tuff-breccia. In a vertical plane, the ideal cross-section is carrot-shaped. Most pipes taper from the surface to depths of 0.6 to 2 miles (1 to 3.2 km) where they pinch to narrow root zones that originate from a feeder dike beneath the root (Kennedy and Nordlie, 1968). At the feeder dike, the kimberlite is massive porphyritic (root-zone or hypabyssal-facies) peridotite rather than a breccia. The porphyry typically has considerable olivine or serpentinized olivine phenocrysts with minor pyroxene in a fine-grained serpentine matrix typical of peridotite.

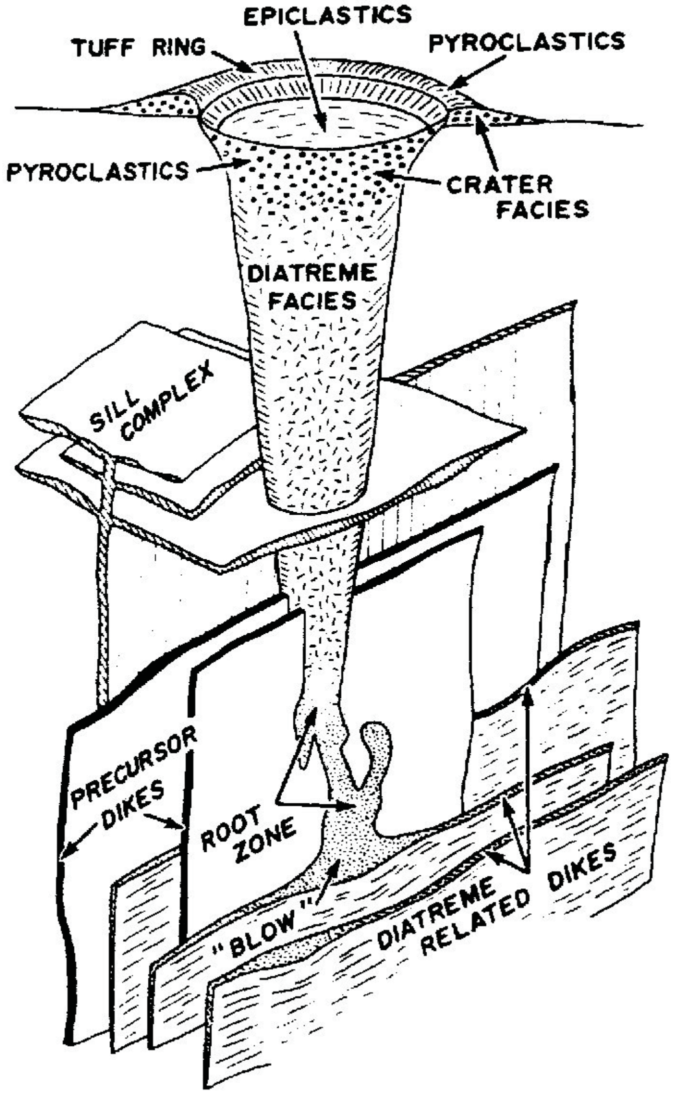

Figure 3. Cross-section of kimberlite pipe showing different facies and the characteristic carat-shaped diatreme (after Mitchell, 1986).

Diamondiferous kimberlite was initially identified in 1870 at the Jagersfontein and Dutoitspan pipes in South Africa. The diamonds were found in deeply-weathered, oxidized kimberlite (referred to as “yellow ground”) that graded into less intensely weathered kimberlite (referred to as “blue ground”). The blue ground is formed of carbonated montmorillonite clay with scattered rounded country rock boulders and mantle nodules. As the kimberlite was mined to greater depth, hard, serpentinized rock was intersected. H.C. Lewis introduced the term *“kimberlite”* in 1887 for diamondiferous rock at the type locality near Kimberley, South Africa that was defined as a porphyritic mica-bearing peridotite.

The magma temperature of kimberlite is hot at depth, but at the point of eruption is strikingly cool. Watson (1967) suggested an emplacement temperature of less than 1100°F (less than 600°C) was necessary to produce coking effects on coal intruded by kimberlite. A much lower temperature of emplacement is supported by the absence of visible thermal effects on country rock adjacent to most kimberlite contacts. Davidson (1967) suggests that the temperature of emplacement may be as low as 390°F based on the retention of argon. Hughes (1982) argues that near-surface temperatures of the gas-charged kimberlite melt may be as low as 32°F (0°C) owing to the adiabatic expansion of CO_2 gas during eruption at the surface and supports that emplacement velocity of gasses and magma which produced the diatreme breccias and crater facies pyroclastics at the surface could have been as high as Mach 3 (2,282 mph)!

Lamproite, another host for diamond, became of major interest following the discovery of a world-class diamond deposit in olivine lamproite in the Kimberley region of Western Australia in 1979. This discovery led to the development of the Argyle mine. Several other diamondiferous lamproites have been described in Australia, Canada, Zambia, Ivory Coast, India, Russia and the United States (Mitchell and Bergman, 1991). Lamproites are known in more than 25 provinces or fields in the world (Mitchell and Bergman, 1991; Coopersmith and others, 2003). Altered diamondiferous leucite lamproite had been described as early as 1967 near Seguela, Ivory Coast (Dawson, 1967). More than a century earlier (in 1827), diamonds had been found in the Majhgawan lamproite in India. Diamonds had also been identified in the Prairie Creek lamproite in Arkansas as early as 1906 (Scott-Smith, 1986, 1989).

Olivine lamproites typically yield higher ore grades than leucite lamproites. But for the most part, lamproites have very low ore grades such as the Mahjgawan olivine lamproite (1.14 Ga) (10 cpht) and the Prairie Creek olivine lamproite (11 cpht) (cpht=carats per hundred tonnes). The Zhenyuan lamproites of the Yangtze craton, China, grade at only 25 cpht (Mitchell and Bergman, 1991). However, there is one very notable exception - the extraordinarily rich Argyle olivine lamproite that yielded some bulk samples as high as 2,000 cpht (carats per hundred tones)!

The pipe morphology of lamproite contrasts with typical kimberlite. Instead of pipes with steep walls that slowly diminish in width with increasing depth, lamproites are characterized by champagne glass-shaped vents filled by tuffaceous rocks often with massive volcanic rock in the core. Many lamproites form distinct cinder cones, flows, and/or maar-like volcanoes (Mitchell and Bergman, 1991). It is important to note that there is a qualitative correlation between diamond and olivine in lamproite. This is seen most everywhere and supported by the Ellendale and Kapamba districts, where diamond grades are consistently higher in olivine lamproites compared to leucite lamproites.

Because of a relatively slow magma ascent rate, diamonds in lamproite often show a variety of morphologies suggestive of resorption and large diamonds are uncommon. At Argyle, for instance, more than 60 percent of the recovered diamonds were irregular-shaped and included macles, polycrystalline forms and rounded dodecahedrons (Shigley and others, 2001). Some diamonds also exhibit evidence of shearing or deformation: ore grades are essentially restricted to preserved pyroclastics in a given vent where magma temperatures declined rapidly following eruption (Scott-Smith, 1986). A potential for substantial ore tonnage exists where there is flaring of the vent. This is well illustrated at the Argyle lamproite in Australia.

Argyle Lamproite

At Argyle (AK1), early reserve estimates of 94 million tons of ore at an average grade of 750 cpht led to its classification as a world-class deposit. At the end of 2004, the reserves at the AK1 pipe were reported at 136.5 million tonnes (290 cpht) and resources at 160.4 million tonnes (270 cpht). Considerable numbers of diamond were found in the adjacent Smoke Creek drainage where mining began in alluvial material in 1983, and the adjacent open pit operation being later commissioned in 1985. The open pit operations are expected to end in 2008 with mining progressing underground for another decade.

Many fabulous gemstones were recovered from Argyle, but a large portion of the diamonds were graphitized and/or partially resorbed, while the largest recovered diamond weighed only 42.6 carats. Overall, the average size of the diamonds is less than 0.1 carat. Even so, at one point, Argyle's annual production totaled 40 percent of the world's production with more than 670 million carats recovered since mine operations began.

Most lamproite-derived diamonds are relatively small and many exhibit *"fancy"* colors. Overall, diamonds from Argyle and Ellendale are relatively small. Macrodiamonds (greater than 1 mm) from Ellendale are dominantly yellow dodecahedra, whereas microdiamonds (less than 1 mm) are colorless to pale-brown, frosted, unresorbed step-layered octahedra. The Argyle diamonds are mostly irregularly shaped, fractured, strongly resorbed dodecahedra or combinations of octahedra and dodecahedra. Almost 80 percent of Argyle diamonds are brown and many of the remaining 20 percent are yellow to colorless. Significant, but rare, are the economically important pink diamonds of which Argyle has accounted for more than 90 percent of the world's *"pinks"*.

A variety of lamprophyres have similarities to kimberlite and lamproite. Some of the lamprophyres have yielded diamond and these potassic rocks are becoming of greater and greater interest for diamonds. Erlich and Hausel (2002) predicted that some lamprophyres would most likely be found that contain commercial amounts of diamond. With greater and greater interest in diamondiferous rocks, a large number of diamondiferous lamprophyres are now being found particularly in Canada.

NORTH AMERICAN DIAMOND DEPOSITS

Diamonds mined from North America prior to 1998 was restricted to minor production from two small operations at Murfreesburo, Arkansas and Kelsey Lake, Colorado. But due to extraordinary exploration efforts, Canada is now a world power in diamonds surpassing South Africa and ranks as the number 3 producer in the world following only Botswana and Russia. It is likely that Canada will soon become the number 2 source of diamonds based on the number of discoveries and exploration expenditures and investments.

The great Ekati diamond mine opened in 1998, and encloses some of the richest kimberlites in the world (fig. 4). But, just after 3 years of operation, the Diavik mine, which opened about 4 years after the Ekati, became Canada's top diamond producer after recovering just under 20 million carats of rough (Robertson, 2006). Canada currently has three major diamond mines in operation - Diavik, Ekati and Jericho, while others are under construction and permitted including Snap Lake, Gahcho Kue and Victor and still other properties in the feasibility stage.

Figure 4. Open at Ekati, Northwestern Territories.

Even though large regions of the United States have potential to host significant diamond deposits, the U.S. will remain unproductive unless effort is made to devote research funding in search of diamond deposits. According to Kjarsgaard and Levinson (2002), exploration over the past several years resulted in the discovery of more than 500 kimberlites (including some unconventional host rocks) in Canada, of which nearly half are diamondiferous. The number of discoveries is now more than double. Some unconventional host rocks include actinolite schist (metamorphosed komatiite? or lamprophyre?) at Wawa, Canada, as well as diamondiferous lamprophyres found elsewhere.

Numerous anomalies have also been identified in the U.S. (fig. 5). In the Wyoming Province (greater than 2.5 Ga) and portions of the Colorado Province (2.5 to 1.6 Ga) collectively referred to as the Wyoming Craton, more than 150 kimberlites and dozens of lamproites and lamprophyres have been found surrounded by vast regions of kimberlitic indicator mineral anomalies and more than 100 structurally-controlled geomorphic depressions with vegetation anomalies of unknown origin. The Wyoming Craton underlies nearly all of Montana and Wyoming, and a portion of northern Colorado. A few dozen kimberlites and lamprophyres have also been found in the Superior Craton in the Great Lakes region of Michigan, Wisconsin and Illinois.

More than 30 percent of kimberlites found in the Wyoming Craton are known to be diamondiferous; although many of the remaining yield favorable geochemistry for diamonds, most have not been tested. Twenty-two *in situ* diamond deposits have been identified in Wyoming; and 20 diamondiferous kimberlites have been found in Colorado (Hausel, 1998) with one described in Montana (Ellsworth, 2000). Diamondiferous host rocks have also been found in the Great Lakes region where as many as 26 kimberlitic and lamprophyric intrusives were discovered in the Michigan-Wisconsin-Illinois region. Eight (about 30 percent) of the kimberlites yielded diamond (Cannon and Mudrey, 1981; Carlson and Floodstrand, 1994). A diamondiferous lamprophyre was also discovered in southeastern Wisconsin (Carlson and Adams, 1997) and a small group of diamondiferous lamproites have been known in Arkansas for nearly 100 years (Hausel, 1995).

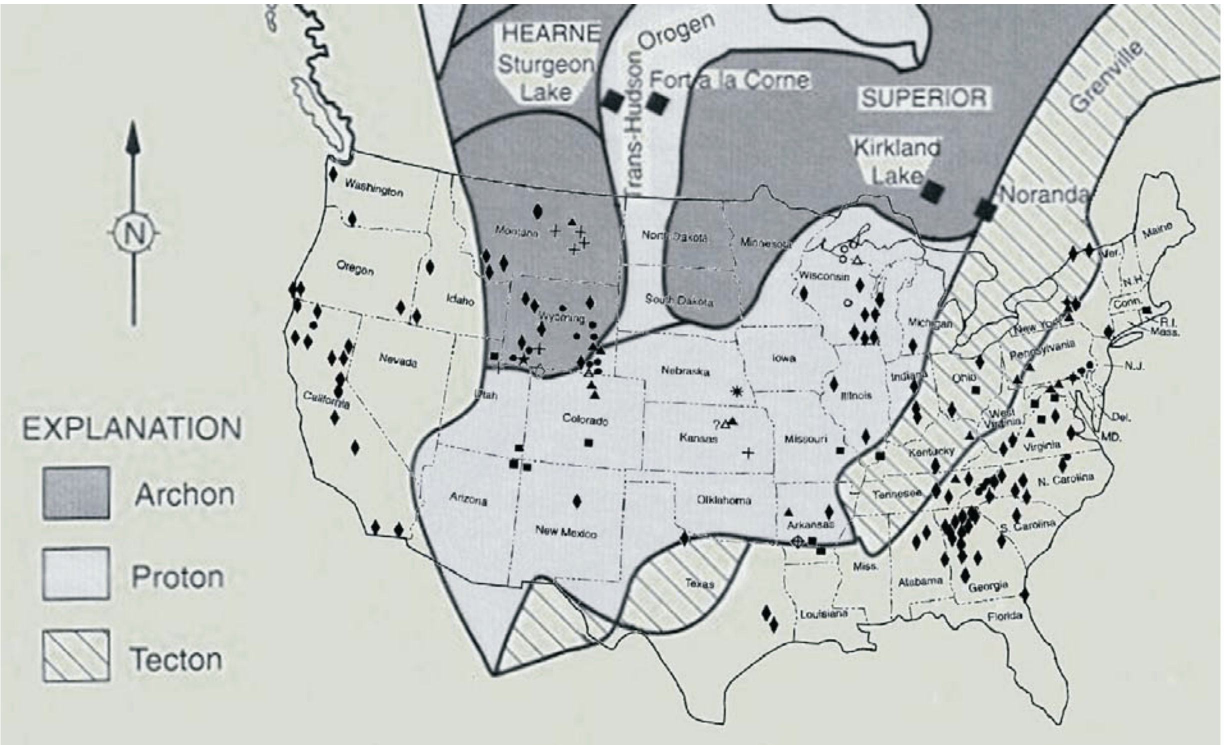

Figure 5. Kimberlite, lamproite, reported diamonds and other anomalies in the U.S. (after Hausel, 1998).

Diamonds were recovered on a small scale at two U.S. localities: Arkansas and Colorado. Diamonds were initially mined at Murfreesboro, Arkansas in the early 1900s from olivine lamproite (about 10 cpht). In the State Line district, two kimberlites were mined in 1996 at Kelsey Lake (Schaffer complex kimberlites) and some attractive diamonds were recovered, including two stones greater than 28 carats in weight and one fragment from a stone estimated to be 3 to 4 times greater in size. The grade was reported at about 15 cpht (Coopersmith and others, 2003). Other kimberlites mined in the district included the George Creek dikes (yielded bulk sample grades greater than 135 cpht and averaged 31 to 46 cpht) and the Sloan Ranch kimberlites (9 to 15.5 cpht). Detrital diamonds have been found scattered throughout the U.S. Most have had little to no follow-up studies and many kimberlites, lamproites and lamprophyres have also been described in the U.S. (Hausel, 1995, 1998).

United States

Alaska

Three detrital diamonds were found in Alaska between 1982 and 1986 in a gold placer on Crooked Creek in the Circle mining district northeast of Fairbanks. The Circle district lies near the fragmented northern margin of the North American craton. No kimberlitic indicator minerals were identified in the placer suggesting that the gems may have originated from lamproite or lamprophyre, or from a distal source. A distal source is supported by the percussion marks and fractures in the diamonds suggesting that the stones had a complex alluvial history (Forbes and others, 1987).

The area in which the diamonds were found is a Tertiary basin. Material in the basin is derived from Late Proterozoic through Late Paleozoic sedimentary and metamorphic rock from the Crazy Mountains to the north and Paleozoic to Precambrian metamorphic and Late

Cretaceous granitic plutonic rocks from the Yukon-Tanana region to the south. Some alkalic igneous rocks are also reported to the south although no kimberlites or lamproites have been identified (Forbes and others, 1987).

More recently, diamonds were described *in situ* in a diamond-bearing tuffaceous maar near Shulin Lake north of Anchorage. However, this occurrence remains to be verified (Casselman and Harris, 2002). Golconda Resources Ltd. and Shear Minerals Ltd. announced that they had recovered 15 microdiamonds and one macrodiamond from 22 pounds of drill core on their Shulin Lake property. The mineralized interval was described as interbedded volcaniclastic and tuffaceous rocks containing olivine and pyroxene (Shear Minerals Press Release, July 8, 2002). The property is located 45 miles (72 km) north of Anchorage (Casselman and Harris, 2002).

Arkansas

Portions of the Gulf Coastal region of Arkansas and Texas are underlain by an Early to Middle Proterozoic basement considered to have low to moderate favorability for diamondiferous lamproite, kimberlite, and lamprophyre. Some diamondiferous lamproites are known in this region. Most notable is the Prairie Creek olivine lamproite located along the edge of the Ouachita Mountains uplift. This lamproite was the site of North America's first diamond mine following a diamond discovery in 1906 near the mouth of Prairie Creek, southeast of Murfreesboro. The pipe yielded more than 90,000 diamonds including the largest diamond found in the United States (40.42 carats), and was later incorporated into the Crater of the Diamonds State Park.

Diamonds recovered from Prairie Creek include 30 percent gems: there has been little attempt to recover microdiamonds (Sinkankas, 1959). Some large diamonds from the property include the Uncle Sam (40.42 carats), the Star of Murfreesboro (34.25 carats), the Amarill Starlight (16.37 carats) and the Star of Arkansas (15.24 carats). Most diamonds are white, yellow or brown, and the most common habit is a distorted hexoctahedron with rounded faces (Bolivar, 1984; Kidwell, 1990). The area is underlain by Cretaceous sedimentary rocks that dip gently to the south (Meyer and others, 1977) and that were intruded by the lamproite at 106 Ma (Late Cretaceous) (Gogineni and others, 1978). The pipe covers an area of approximately 73 acres (30 ha) and consists of breccia, tuff and hypabyssal olivine lamproite (Miser and Ross, 1922; Bolivar, 1984). Nearly all diamonds have been recovered from breccia facies lamproite, whereas the other magmatic facies are diamond poor. Gogineni and others (1978) report pyrope compositions to be equivalent to G9 calcic-chrome pyropes, and Fipke and others (1995) identified only one sub-calcic G10 pyrope from the lamproite. None of the chromite analyses from the pipe yielded favorable geochemistry for diamonds. Thus based on the indicator mineral geochemistry, this would be considered as a very poor target for diamonds, if considered at all. Even so, the pipe has been more productive than what the geochemistry would suggest.

Five other lamproites have been reported nearby and, due to very thick vegetation and a long history of erosion, the probability of other undiscovered and hidden lamproites is likely. Other lamproites found 2 miles (3 km) north of Prairie Creek include the Kimberlite, American, Black Lick, Twin Knobs and Twin Knobs 2 intrusives (Krol, 1988; Mike Howard, written communication, 1996). Both the Kimberlite lamproite and the American lamproite have yielded some diamonds (Miser, 1914; and Miser and Ross, 1922).

Other ultramafic rocks of lamproitic or lamprophyric affinity have been reported a few miles east of Prairie Creek and about 3 miles (5 km) south of Corinth. Another intrusive of possible interest is the Blue Ball kimberlite dike located 24 miles (38 km) southwest of Danville (Salpas and others, 1986; Hausel, 1998). Little information is available on this intrusive.

Wyoming Craton

Diamonds were found *in situ* in the Colorado-Wyoming region in 1975 in a Wyoming kimberlite (McCallum and Mabarak 1975). Since 1975, essentially every kimberlite in this district has yielded diamond. Even so, some kimberlites still have not been bulk sampled and several geophysical anomalies interpreted as blind diatremes remain inexplicably unexplored. Another group of blind diatremes were found a short distance further south along the border also using an airborne geophysical survey (Tony Barringer, personal communication).

Of the bulk samples taken in the district, grades ranged from less than 0.5 to 135 cpht with 30 to 50 percent gemstones with more than 130,000 diamonds recovered. The 135 cpht bulk sample had been contaminated by considerable granitic country rock, thus the true ore grade of the kimberlite could have been considerably higher. Two episodes of kimberlite magmatism was recognized (Early Cambrian & Early Devonian) along a region extending 3 miles (5 km) north into Wyoming and at least 10 miles (16 km) south into Colorado (Hausel, 1998) and possibly more.

State Line district

The most productive property in the Wyoming Craton area to date was the Kelsey Lake mine in Colorado. Commercial production began in 1996 with a mill capacity of only 25,000 carats/year. The mine was developed on two Kelsey Lake kimberlites (KL1 and KL2) which had been initially mapped as the Schaffer 1, 2, 6, 7, 8, and 9 by Eggler (1967). The kimberlites are irregular-shaped pipes and fissures with diatreme facies kimberlite and zones of hypabyssal facies and minor crater facies. An apparent Devonian age on the Kelsey Lake kimberlites is in agreement with Early Devonian and/or Cambrian isotopic ages for most other pipes found in the Colorado-Wyoming kimberlite province (Coopersmith, 1993, 1997; Hausel, 1998).

The mine yielded many high-quality diamonds. Some of the larger stones included 6.2, 9.4, 10.48, 11.85, 14.2, 16.9, 28.18, and 28.3 carat gems. One broken fragment was estimated to have fragmented from a larger stone of 80 to 90 carats (Howard Coopersmith, personal communication, 1999). The diamonds exhibit predominantly octahedral habit and are colorless with some honey-brown gems (Coopersmith and Schulze, 1996). The 28.18 carat diamond was cut to produce the largest faceted diamond found in the U.S. The finished stone weighed 16.8 carats and had an estimated value of more than US$250,000 (Denver Post, September 25, 1997). A 28.3 carat diamond, also recovered from Kelsey Lake, was cut into a 5.39-carat gemstone that sold for $87,000 (Paydirt, 1996).

Two open pits were developed to 125 feet (38 m) deep. The ore averaged only about 5 to 15 cpht (Coopersmith and others, 2003), but the high diamond value and relatively low capitalization costs allowed the operation to apparently start out favorably until operations terminated due to legal problems. The property was later reclaimed in 2005.

The Kelsey Lake kimberlites are not mined out and considerable unmined ore remains in place. Resources were established at 16.9 million tonnes to a depth of 320 feet (100 m) (Coopersmith, 1997). The mill was also inefficient as it rejected an unknown amount of diamonds to its tailings including everything greater than 40 carats in weight! During later testing of the mine tailings by Roberts Construction Company, the very first sample yielded diamonds up to 6 carats in weight. Thus the possibility that even much larger diamonds were lost during the operation is likely.

Kimberlites in the State Line district surrounding mines show distinct structural control. Thus, exploration for additional kimberlites is enhanced by field mapping of structural trends. All kimberlites in the district have been deeply eroded such that diatreme and hypabyssal facies kimberlites are exposed at the surface. This implies that a very large diamond budget was carried downstream during periods of erosion (Hausel, 2004). The probability that diamond placers have been overlooked is highly likely. For example, detrital diamonds including a 6-carat stone was found in Fish Creek, Wyoming, and smaller diamonds were found in placers south in Colorado. There has been very little to no exploration of placers or paleoplacers, and absolutely no systematic sampling.

Iron Mountain district

A second major kimberlite district lies 45 miles north of Cheyenne near Chugwater, Wyoming (fig. 6). This district, known as Iron Mountain includes the nearby Indian Guide kimberlites. The district forms a large cluster of kimberlite dikes, sills, blows, structurally controlled depressions and other anomalies in the Sherman granite (1.4 Ga) and Laramie Range anorthosite (1.5 Ga). The kimberlites form continuous anatomizing (Early Devonian) dikes with some blows. Portions of the dike complex were mapped over a strike length of 5 miles (8 km) prior to the kimberlites disappearing under Phanerozoic and Quaternary sediments at either end of the complex. Thus the complex extends for an unknown distance beyond both extremities under younger sedimentary rock (Hausel and others, 2000). There is also considerable Quaternary (Tertiary?) boulder conglomerate cover within the district and kimberlites were mapped to the edge and presumably continue under the conglomerate. Farther west is a group of structurally controlled depressions along strike that are possibly additional kimberlites (Hausel and others, 2003). These remain unexplored for diamonds. Much of the kimberlite in the district is hypabyssal with some diatreme facies and a group of kimberlites in the northwestern portion of the district, known as the Indian Guide kimberlites, yielded some diamonds including a 0.3 carat stone (Coopersmith and others, 2003). Essentially, all kimberlites in this district yielded diamond stability minerals (Hausel and others, 2003), and in many cases the geochemical signatures are essentially the same as that for the Kelsey Lake diamond mine.

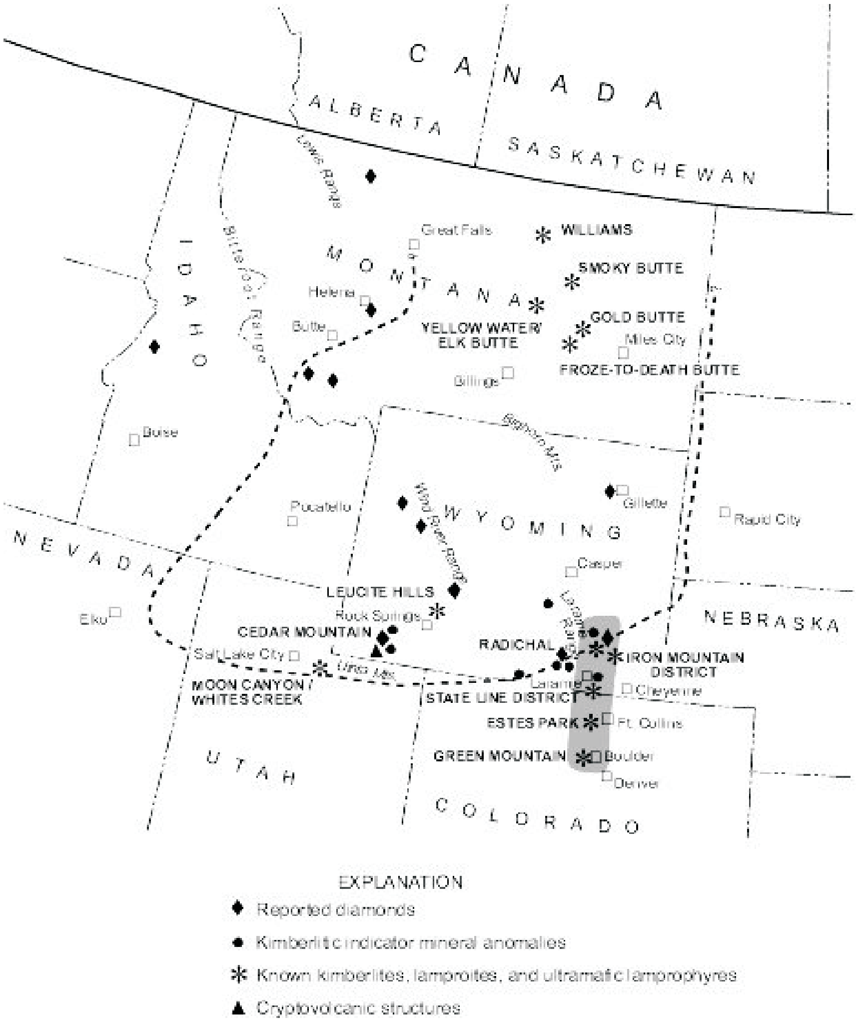

Figure 6. The Wyoming Province Archon within dashes surrounded by Proterozoic accreted terrains as well as locations of anomalies of interest (i.e., kimberlites, lamproites, indicator mineral anomalies, etc., after Hausel, 1998). Very large regions of the Archon remain unexplored including regions considered to have high potential for significant diamond occurrences, such as the older core of the craton in the vicinity of the Granite and Wind River Mountains.

Middle Sybille Creek

Northwest of the Iron Mountain district is the Middle Sybille Creek district where a single kimberlite blow (Radichal) was found in 1980 (Hausel and others, 1981). The kimberlite is surrounded by more than 4 dozen strong kimberlitic indicator mineral trails that provide evidence for other hidden kimberlites in that region. One of the anomalies (referred to as the *Grant Creek anomaly*) lies along Grant Creek at the eastern edge of the district where a few hundred indicator minerals were recovered from stream sediment samples that suggest a proximal source. Nearby, a limestone xenolith (?) was identified in the Laramie anorthosite (1.5 Ga). This limestone is either out-of-place or represents a Paleozoic outlier similar to those found in the State Line district in the early 1960s that were later proven to be kimberlite. This is referred to this as the “Grant Creek outlier”.

Eagle Rock-Happy Jack district

The Eagle Rock-Happy Jack district was discovered by the WSGS during stream sediment sampling between Laramie and Cheyenne (Hausel and others, 1988). Dozens of indicator minerals were recovered along several drainages indicating the presence of hidden kimberlites. To the south, the author recently discovered a group of circular depressions containing considerable carbonate-rich sediment enclosed by Sherman Granite (1.4 Ga).

Indicator mineral anomalies (pyrope garnet, chromian diopside, picroilmenite, chromite, and/or diamonds)

Between the Iron Mountain and State Line districts, as well as several miles north and along the eastern flank of the Medicine Bow Mountains, more than 300 kimberlitic indicator mineral anomalies were discovered: very few have ever been traced to their source (Hausel and others, 1988). Numerous other KIM anomalies were identified by Cominco American in the same region (Howard Coopersmith, personal communication, 1990).

KIM anomalies are widespread and have been identified in the Laramie, Hartville, Sierra Madre and Seminoe Mountains and in the Greater Green River Basin in southern Wyoming, and in the Bighorn Basin, the southern Bighorn and Owl Creek Mountains, and the Powder River Basin of northern Wyoming. KIM anomalies are also reported in the Front Range of northern Colorado, in the Uintah Mountains of northeastern Utah and in the Sweet Grass Hills of Montana. The presence of several hundred KIM anomalies along with geophysical and remote sensing anomalies support that the Wyoming Craton has been intruded by major swarms of kimberlitic and related intrusives.

Green River Basin

One of the major KIM anomalies was described McCandless and others (1995) in the Green River Basin of Wyoming. Five diamonds were found in the early 1980s in a drainage running from the flank of Cedar Mountain within this region. Later, a group of 10 mafic lamprophyric breccia pipes and dikes were discovered in this drainage, and many others were mapped in the region by Amselco. The pipes lie along a 5- to 10-mile-long (8-16 km), northerly-trending lineament in the Bridger Formation (Eocene). Samples recovered from the pipes yielded some diamonds (Hausel and others, 1999) and Guardian Resources later reported the discovery of two additional breccia pipes nearby (Press Release, Guardian Resources, 1997). Diamonds were also recovered by Anadako from these intrusive.

Several alluvial diamonds were found in a nearby drainage (Guardian Resources Press Release, Sept. 24, 1996). The Cedar Mountain pipes and dikes contain numerous KIMs that are geochemically similar to those in the Bishop Conglomerate (Oligocene) and in anthills to the north, many of which are gem quality. The pipes only account for a small portion of the indicator minerals in this region.

Leucite Hills lamproites

The largest lamproite field is northeast of Cedar Mountain and north of the towns of Superior and Rocks Springs. Twenty-two lamproites were mapped in this area and the field remains unexplored for diamonds. Some gem-quality peridot was found in the northeastern portion of the volcanic field, along with some diamond-stability chromites (Hausel, 2006). The possibility of hidden, diamondiferous olivine lamproite in the Leucite Hills needs to be investigated.

Many other anomalies have been identified in Wyoming including KIM anomalies in the Seminoe Mountains and the Bighorn Basin, and in the Medicine Bow Mountains. One very interesting anomaly identified by the WSGS several years ago is a Tertiary-Quaternary conglomerate along the north flank of the Seminoe Mountains. This conglomerate has occasional pebbles of tawny-colored banded iron formation typical of that found at the western edge of the Seminoe Mountains greenstone belt (Hausel, 1993). Panned samples of the dry conglomerate in the flats near the Miracle Mile yielded gold as well as pyrope garnet. Samples from both sides of the North Platte River yield lilac to purplish garnets that were tested for geochemistry. All pyrope analyses have yielded diamond-stability geochemistry typical of sub-calcic chrome pyropes (G10). The possibility of finding diamonds in this region is very high.

Montana

Detrital diamonds have been found in Montana in the northern portion of the Wyoming craton, along with numerous potential host rocks (alnöite, peridotite, monchiquite, lamproite and kimberlite) (fig. 5). Several potential host rocks are found within the central alkalic province in eastern Montana, and a few lamproites are reported in western Montana including the Ruby Slipper (Pete Ellsworth, personal communication, 1996). Two diamonds were found in gravels of the Etzikom Coulee in the Milk River drainage north of the Sweet Grass Hills in northern Montana (0.14 and 0.17 carats) (Lopez, 1995). The occurrence lies near a buried magnetic anomaly aligned with presumed kimberlitic rocks in Alberta.

This extensive field of lamproites, lamprophyres and kimberlites in eastern Montana have trace amounts of KIMs (Fipke and others, 1995). Some interesting targets in this region include a belt of ultramafic lamprophyre and kimberlite diatremes in the Grassrange Field, east-central Montana. The area was highly recommended (Hausel, personal field notes, 1994) as having high potential for diamonds and within a few years following this recommendation, the Homestead kimberlite was discovered and proven to be diamondiferous (Ellsworth, 2000). This kimberlite sits near an extensive breccia pipe known as Yellow Water Butte that is formed of massive to brecciated olivine-phlogopite-diopside-carbonate lamprophyre with massive hypabyssal olivine lamprophyre facies (Doden, 1996).

Hypabyssal facies kimberlites are found near Landusky north of the Grassrange Field. These include four closely-spaced diatremes in the eastern part of an east-northeasterly trending swarm of ultramafic alkalic diatremes, dikes and plugs (46 to 51 Ma) in the Missouri Breaks area of north-central Montana that are referred to as the Williams kimberlites. Analyses of garnets from the kimberlites indicate compositions equivalent to G-9 (Hearn and McGee, 1983) and P-T estimates from co-existing orthopyroxene-clinopyroxene pairs in some of the peridotite nodules indicate some nodules may have originated from the diamond stability field (Fred Barnard, written communication, 1994).

West Coast

The west coast of the U.S. and Canada may provide some very interesting unconventional targets for diamonds. Many diamonds were found in the past during gold placer mining in California, Oregon and Washington. California, in particular, was a good source for diamonds in the gold rush days. Some historical gold placer mines north of Oroville, California in the Round Mountain area yielded diamonds as a by-product of gold mining between 1853 and 1918. About 400 diamonds and 600,000 ounces of gold were recovered on the Feather River (Hill, 1972). Kunz (1885) reported diamonds were found in all of the northern counties of California drained by the Trinity River in the vicinity of Coos Bay, Oregon; and on the banks of the Smith River of Del Norte County, California. Five diamonds were also recovered from a tributary of the Trinity River in Hayfork Creek. One found in 1987 weighed 32.99 carats (Kopf and others, 1990). Sinkankas (1959) reported that microdiamonds were found in the black sands of the Trinity River near its junction with the Klamath River, and pyrope garnet and chromian diopside were described from the Trinity River (Kopf and others, 1990). Chromian diopside-bearing serpentinites were later discovered in this area (Hausel, personal field notes 1995).

The presence of an active Benioff zone in California provides a mechanism to develop over-pressurized magmas at depth and possibly provide a source for the diamonds. Breccia pipes from such magmas may have been found at Leek Springs and at another undisclosed locality in the Sierra Nevada of California. Both pipes contain some diamond-stability minerals. The possibility of other breccia pipes in this region needs to be considered.

Diadem Resources reported discovery of a cluster of dikes including a 1,875 by 188 m (6,000 x 600-foot-wide) "dike" after following an indicator mineral trail upstream from a historic diamond placer at Leek Springs (Northern Miner, 1/29/96). Drill cuttings from a 120 foot (37 m) zone of "lamproite" yielded 235 diamond fragments (Northern Miner, 4/20/96). At another breccia pipe in the Sierra Nevada, the diatreme has clasts of serpentinite along with some diamond-stability indicator minerals typical of mantle peridotite (Lynn O'Rouke, personal communication).

Great Lakes Region

A group of kimberlites in the Michigan-Illinois area in the Great Lakes region intrude the Superior Province, which is an Archean craton underlying much of Minnesota and eastern South and North Dakota continuing north into Canada. The Superior Province is bounded on the west by the Trans-Hudson Orogen and a Proton of Early to Middle Proterozoic basement rock to the east and south suggesting this region to have moderate potential for diamond discoveries.

The Early to Middle Proterozoic basement along the margin of the Superior Archon is bounded by Late Proterozoic rocks of the Grenville Tecton further to the east. The Grenville Tecton extends into eastern Michigan and Indiana. Several diamonds (including some sizable stones) were recovered from the Great Lakes region (Hausel, 1995, 1998). These were thought to have been transported from Canada by continental glaciers during a past ice age. This assumption has come under question since the discovery of several post-Ordovician kimberlites in Michigan. A few dozen kimberlites and lamprophyres have also been described within the Superior Craton in Michigan, Wisconsin and Illinois. Eight kimberlites in Michigan yielded diamond (Cannon and Mudrey, 1981; Carlson and Floodstrand, 1994) and a diamondiferous ultramafic lamprophyric breccia was discovered in southeastern Wisconsin (Carlson and Adams, 1997). At least 26 kimberlites have been found in Michigan, Wisconsin and northern Illinois. Eleven magnetic anomalies were also detected that are suggestive of buried diatremes. Michigan also has some Paleozoic outliers that are completely surrounded by Proterozoic rocks that are interpreted as cryptovolcanic structures that are possibly kimberlite pipes.

One kimberlite found near Crystal Falls, Michigan, lies one mile (1.6 km) west of Lake Ellen near the Wisconsin border. This kimberlite (Lake Ellen pipe), is poorly exposed but yields a strong positive magnetic anomaly that suggests the presence of a 650 to 950 feet (200-290 m) diameter kimberlite with a surface area of 20 acres (8.1 ha). The kimberlite was emplaced in Proterozoic volcanic rocks and has abundant Ordovician(?) dolomite xenoliths. Diatreme facies kimberlite at Lake Ellen contains olivine, pyroxene, mica, pyrope and magnesian ilmenite in a fine-grained serpentine matrix (Cannon and Mudrey, 1981). Another kimberlite (Michgamme), lies a short distance northwest of the Lake Ellen intrusive along the Michgamme Reservoir shoreline (Carlson and Floodstrand, 1994).

Northwestern Wisconsin is underlain by basement rocks of the Superior Province while Proterozoic age rocks underlie the remainder of the state. Since 1876, 25 diamonds were found in southern and central Wisconsin. All were found in Pleistocene glacial deposits or Holocene river gravel. Other diamonds were recovered in a diamondiferous ultramafic lamprophyre (melnoite) known as the Six-Pak diatremes that was discovered by Ashton with airborne magnetics. The diatreme was drilled: it has 50 acre (20 ha) surface area and consists of hypabyssal facies lamprophyre with a typical kimberlitic mineral suite including calcic pyrope garnet (G9). Several small diamonds were recovered from the intrusive. The intrusive lies in the outskirts of Kenosha in southeastern Wisconsin (Carson and Adams, 1997). Many other kimberlites, lamproites and lamprophyres have been identified in the U.S. The reader is referred to Hausel (1995, 1995a, 1998) for these.

Canada

Canada is undergoing a major economic evolution. Many kimberlites and other potential diamondiferous host rocks have been identified over large regions of the North American Craton in Canada (fig. 7). Most of the discoveries have been made since the early 1990s. The number of discoveries and the variety of host rocks as well as the incredible capital investment will change fundamental concepts on diamond exploration. The scenario has resulted in one of the greatest economic evolutions in history. Within a very short period, Canada became the world's number three producer of gem-quality diamonds. Prior to 1998, Canada did not produce a single commercial natural diamond. Today, only Namibia and Russia out-pace Canada. But within the next decade, Canada is expected to become the number two diamond producer in the world and may even surpass Namibia within the foreseeable future.

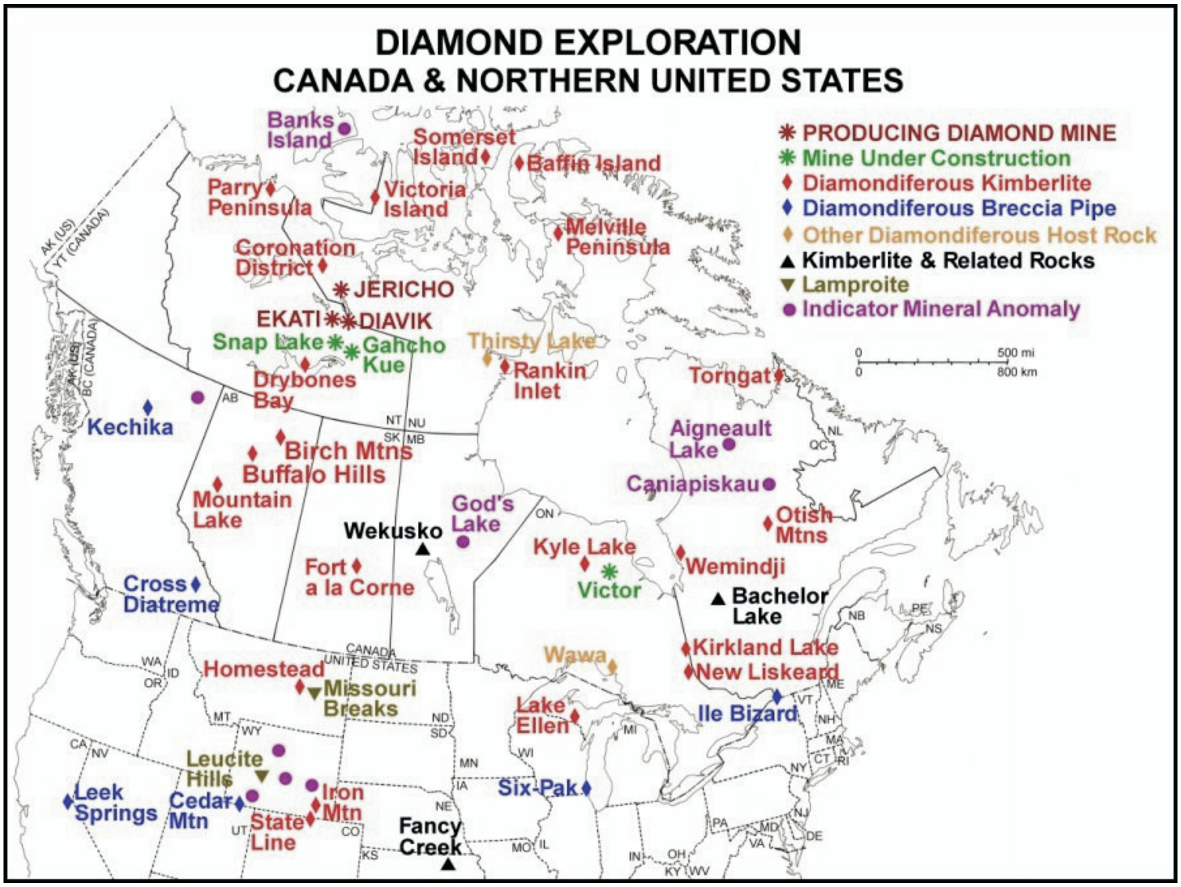

Figure 7. Location of principal diamond districts, fields and anomalies in North America (compiled by Wayne M. Sutherland and the author).

The diamond discoveries span the North American craton from one end of Canada to the other. One interesting anomaly is that the discoveries essentially end at the U.S. border. This is a political anomaly, not a geological phenomenon.

Alberta

Exploration in Alberta resulted in the discovery of several kimberlites, lamprophyres, widespread KIM anomalies and magnetic anomalies. Both magnetics and electromagnetics have proven invaluable in the search for hidden kimberlite in this region. Widespread KIMs have been identified in Alberta. The Alberta Geological Survey reports widespread anomalies from the Canadian-Montana border northward to the Northwest Territories, with extensive anomalies in the central portion of the Province (Alberta Geological Survey, 2004). The data suggests the presence of hidden kimberlites and related host rocks.

One group of kimberlites were discovered along a northeasterly trend paralleling two major shear structures near the north-central portion of the province. These occur at (1) Mountain Lake northeast of Grande Prairie, (2) Buffalo (Head) Hills northeast of Mountain Lake and (3) in the Birch Mountains further to the northeast. Many of the kimberlites in northern Alberta yield 70 to 85 Ma ages (Simandl and others, 2005).

At (1) Mountain Lake, the diatremes are lamprophyres. The Mountain Diatreme was discovered in 1973 and initially interpreted as kimberlite. However, recent analyses suggest it is a hybrid with geochemical affinities for basanite (olivine potassic basalt), olivine minette, alnöite and melilitite. Compared to the Buffalo Hills and Birch Mountains kimberlites, the Mountain Lake diatreme has higher SiO2, Al2O3, Na2O, K2O, Na2O/K2O, Ga, Rb and peralkalinity index, and lower MgO, Nb, LREE, and Sr. The chemistry implies high potassic, alkali, ultramafic rock (Eccles, 2002).

In 1983, a sample of the lamprophyre taken by Superior Minerals yielded two microdiamonds from a 77-lb (35 kg) sample and 8 or 9 microdiamonds were recovered from crater facies outcrops at the surface (Casselman and Harris, 2002).Two pipes are known in this area. The Mountain Lake diatreme is 118 miles (190 km) southwest of Norman Wells, Northwest Territories in the Mackenzie Fold Belt. It forms a 1,970-foot-diameter (600 m) pipe that intrudes Upper Cambrian to Middle Ordovician limestone. The diatreme contains picroilmenite, pyrope and chrome-diopside xenocrysts similar to the DK pipes at Cedar Mountain in the Green River Basin of the Wyoming Province. The Mountain diatreme has a central core of dark green autolithic breccia with lesser country rock xenoliths. The matrix is composed of chlorite, phlogopite and carbonate with minor serpentine, tremolite and opaques. K-Ar dating of phlogopite returned a 445 Ma age for the intrusive.

The Buffalo Hills cluster to the northeast is of current interest due to discovery of 36 diamondiferous pipes within a cluster of 38 kimberlites. Three (K14, K91 and K252) have yielded bulk sample tests of greater than 11 cpht; the K252 kimberlite yielded an initial test of 55 cpht and is of potential economic interest (Alberta Geological Survey, 2004; Cummings, 2006). The Buffalo Head Hills are underlain by Early Proterozoic crystalline basement with possibly some Archean basement of the Buffalo Head Craton. The regional setting was favorable for emplacement of kimberlite during periodic tectonic activity associated with movement along the Peace River Arch (Alberta Geological Survey, 2004; Cummings, 2006).

Samples from the region yielded significant numbers of KIMs including olivine, pyrope garnet, chromite and picroilmenite. Some of these were collected well north of the northernmost known Buffalo Hills kimberlite indicating a strong likelihood that undiscovered kimberlites lie to the north. In addition, some geophysical anomalies within the cluster are characteristic of hidden kimberlite.

At least three distinctive volcaniclastic units are recognized in the Buffalo Hills kimberlites, two are primary pyroclastic deposits that are not normally preserved in most kimberlites. The pipes are distributed over a 2,300 mi^2 (6,000 km^2) area and intrude Proterozoic Buffalo Head Terrain. The kimberlites erupted through Proterozoic basement, Devonian sedimentary and Cretaceous sedimentary rock, but were covered by Quaternary till (Boyer and others, 2005).

Volcaniclastic crater facies kimberlite in the district indicates very little erosion has occurred since diatremes emplacement. The crater facies includes well-sorted, ash-size fine-grained, olivine-rich layers interbedded with lapilli-size fragment-rich layers. Cross-stratified and finely bedded deposits are similar to those formed by basal surge and pyroclastic ash fall. Some accretionary fragments with multiple magmatic rinds thought to have formed during a series of eruptions are typical of proximal crater-fill and pyroclastic ash falls. Some poorly-sorted, subtly bedded, crystal-rich kimberlite is depleted in fine-grained matrix material (Boyer and others, 2005).

The Buffalo Head Hills and Birch Mountain diatremes are chemically similar to Group I kimberlites. Of the two, the Buffalo Hills kimberlites have the highest MgO, Cr, and Ni, the lowest Al2O3, SiO2, V, Y, Pb, Sr and Ga content, and have geochemical signatures similar to primitive kimberlite in the Northwest Territories. In addition, a high proportion of the Buffalo Head Hills kimberlites are diamondiferous (Eccles, 2002).

Diamonds recovered from the K11, K91 and K252 kimberlites in the Buffalo Hills cluster are mainly colorless and transparent: most have resorbed octahedral habits. The garnet, olivine and pyroxene inclusions indicate a presence of both eclogitic and peridotitic diamonds. The data supports that a lithospheric mantle beneath Buffalo Hills is dominated by an eclogitic component similar to many younger diamond-bearing areas around the world. The presence of rare majoritic garnet inclusions in some diamonds supports that some diamonds were formed in very deep mantle source region (Eccles, 2002).

At least nine kimberlites have been identified in the Birch Hills cluster northeast of the Buffalo Head Hills: two of which have yielded diamonds. The Birch Mountains kimberlites are more evolved than the Buffalo Hills kimberlites and have lower SiO2, Ni and MgO and higher Fe2O3, TiO2, Nb, V, Sc, Zr, Hf, Y, Ba, Rb, LREE, Ga and Pb. Hence, whole-rock geochemistry of these kimberlites is similar to Group IB South African kimberlite. One kimberlite, known as the Legend, is a 1,640 to 2,625-foot (500-800 m) diameter multiphase kimberlite. The Legend Kimberlite lies beneath 42 feet (12.8 m) of overburden. Four microdiamonds were recovered from an 896-lb (406 kg) sample (Eccles, 2002).

British Columbia

Much of British Columbia is underlain by an unconventional terrain for primary diamond deposits. However, recent studies in the extreme northeastern portion of the province suggest that part of that region may be underlain by a structurally disturbed fragment of the North American Craton. Even though much of British Columbia is considered unfavorable for *in situ* diamond deposits based on traditional diamond exploration concepts, diamonds have been recovered from a group of breccia pipes, many with classical KIMs. These intrude the Cordilleran belt along a NNW-trend. Lithologies include alkalic basalts, and alkalic and ultramafics lamprophyres. Only a few true kimberlites are reported in British Columbia. Even so, microdiamonds have been recovered from some pipes.

Many anomalies have been identified near the Alberta border north of Montana and further north in northern British Columbia. The known kimberlites and lamprophyres have yielded age dates of 391 to 410 Ma for the HP pipe to 240 Ma for the Cross diatreme (Simandl and others, 2005). Of 58 samples of alluvium, regolith and bedrock collected in extreme northeastern British Columbia in the Etsho plateau near Ft. Nelson and Dawson Creek, 38 contained kimberlitic indicator minerals supporting a likelihood of hidden pipes. Some indicator minerals yielded diamond-stability geochemistry and one enclosed a microdiamond inclusion.

Nearly all of diatremes lie along a north-south 54 by 12 mile (87 x 19 km) trend within the Rocky Mountains Uplift. This region is remote and rugged supporting that other discoveries will likely be made with continued exploration (Roberts and others, 1980; Grieve, undated). Many of the diatremes were emplaced in Cambrian to Permian carbonate and clastic sedimentary rocks of the Foreland and Intermontane Belts near the west coast of Canada (Simandl, 2003). This area is characterized by thrusts and associated folding. All of the diatremes were emplaced in Middle Devonian and older strata while the Cross diatreme in the Elkford cluster in the southeastern corner of the province was emplaced in Permian bedrock. The terrain is not what would be anticipated for primary conventional diamond models that require cool, stabilized, cratonic cores (Archons) with thick keels. Instead, this region is geologically unstable and has been subjected to considerable deformation with displaced and accreted terrains.

Kechika Group

The Kechika River group includes the Xeno pipe that lies at the northern end of Dall Lake in the Kechika Range of the Cassiar Mountains. The property was originally acquired for rare earths associated with a mafic alkalic igneous complex that is underlain by quartzite of the Lower Cambrian Atan Group, chlorite-sericite schist, phyllite, marble and dolomite of the Cambrian-Ordovician Kechika Group, and by siliceous tuff, chert, sandstone and argillite of the Ordovician to Silurian Sandpile Group. The rare earths are hosted by alkalic igneous complex that forms a west-northwest trending belt of cogenetic syenites, trachytic volcanics and carbonatites that have been traced for 12.5 miles (20 km) along strike and is a few hundred feet to a few miles wide. At the southern end of this belt, a diatreme was discovered with a variety of igneous and sedimentary (quartzite and carbonate) xenoliths and chrome-spinel xenocrysts in a pale green, carbonate-rich tuffaceous matrix. Exploration in 2002 identified a nearby lamprophyre dike that varies in width from a few to over 160 feet (49 m) exposed intermittently along a 1.6 mile (2.6 km) strike length. A 70-lb (32 kg) sample collected from the dike yielded a transparent, green microdiamond (0.38 x 0.30 x 0.25 mm). The Kechika River diatreme within the Kechika Range lies west of the Rocky Mountain trench has geochemically affinity for alkalic lamprophyre.

The Ospika pipe to the south of Kechika River (north of Mackenzie) is complex breccia with at least 5 intrusive events. The breccias has xenoliths, cognate nodules and phlogopite, titaniferous augite, rare altered olivine and bright green diopside in aphanitic carbonate matrix. The pipe is classified as an ultramafic lamprophyre (aillikite) based on petrography and whole rock geochemistry (Ijewliw and Pell, 1996). A microdiamond was reportedly recovered from breccia in a carbonatite complex in the Kechika area.

Golden Field

A group of diatreme breccias and dikes are reported at five localities further south, in the Golden field. These are located at Bush River, Mons Creek, Valenciennes River (Mark diatremes), Lens Mountain (Jack diatreme) and Campbell. The Bush River breccia and dikes have been classified as olivine kersantites (calc-alkalic lamprophyres) based on mineralogy, although they have an affinity for more alkaline chemistry. Diatremes and dikes in the Mons Creek and Valenciennes

River are altered with pseudomorphs of serpentine after olivine, clinopyroxene, biotite and plagioclase and are classified as camptonites (alkalic lamprophyres). The Lens Creek diatreme may be lamproitic, and the HP pipe south of the Campbell Ice field consists of limestone clasts, quartzite, clasts of plutonic rock with autoliths, megacrysts and phenocrysts of clinopyroxene (chrome diopside), melanite garnet, biotite spinel and apatite in a groundmass of calcite, chlorite, serpentine, talc and pyrite and is classified as aillikite (Ijewliw and Pell, 1996). Simandl (2003) reports that diamonds were recovered from samples from the Jack (Lens Mountain) and Mark (Valenciennes River) diatremes.

Bull-Elk Creek Field

More than 40 breccia pipes and dikes are found south-southeast of the Golden Field near Cranbrook in the Bull-Elk Creek field. These are primarily tuffaceous intrusives with vesicular lapilli, clinopyroxene, olivine, calcite, and spinel in a groundmass of carbonate, chlorite, talc and minor plagioclase.

Summer diatremes

The Summer diatremes, 24 miles (38 km) northeast of Cranbrook, lie near the intersection of Galbraith and Summer Creeks. One known as the Quinn diatreme lies near the head of a tributary of Quinn Creek, 36 miles (58 km) northeast of Cranbrook. This diatreme intrudes Ordovician-Silurian Beaverfoot-Brisco Formation carbonates and has gray-green matrix with small clasts and phenocrysts of olivine and spinel (less than 5 mm). In thin section, angular quartz and feldspar, volcanic fragments, carbonate, argillaceous material and serpentine occur in carbonatized groundmass. Xenoliths in the breccia include well-rounded limestone, argillite, quartzite, granite and rare ultrabasics (Grieve, undated). Simandl (2003) reported that macrodiamonds were extracted from the Cranbrook cluster, the Bonus and the Ram 5 and 6 diatremes. The Ram 6 is located north of Elkford and reported to be diamondiferous and possibly kimberlitic (Allan, 1999).

Elkford kimberlites

The Cross diatremes in southeastern British Columbia is located near Elkford (fig. 7). This diatreme was initially reported in 1957 on the north side of Crossing Creek valley. It covers a surface area of 225 by 190 feet (69 x 58 m) and is composed of intrusive breccia in a shear zone in Permian Rocky Mountain Group shale, limestone and chert. No thermal metamorphism is visible along the intrusive contact. The breccia matrix is a bluish-green, calcareous groundmass enclosing phenocrysts and megacrysts of phlogopite, altered olivine, hematite, calcite, chromian diopside and reddish-brown pyrope-almandine garnet with rounded to subangular xenoliths of limestone, argillite, serpentinite and peridotite. Reconnaissance exploration was not initiated until after the Cross diatreme was described as kimberlite in 1976. Geochemical analyses support that it is kimberlite, and four other kimberlites are apparently found in the region (Ijewliw and Pell, 1996).

Portions of the field are underlain by blueschist and eclogite facies rocks interpreted as subducted-related. Some diatremes in British Columbia are weakly diamondiferous possibly from sampling material from a paleo-subduction zone. The breccia matrix or magma type for the British Columbia breccia pipes is not well defined, similar to the subduction related breccias identified in California. The majority of diatremes in British Columbia are ultramafic lamprophyres while the Cross is kimberlitic (Grieve, Undated).

Labrador

At least four areas in northern Labrador within the Nain Province (Archean) have been identified that have rocks of apparent kimberlitic to lamprophyric affinity. These include (1) Capes Aillik-Makkovik dikes and pipe, (2) the Ford's Bight diatreme, (3) the Saglek dikes and pipes, and (4) the Torngat Mountains dikes. Groups 1, 2, and 3 are described as kimberlites, and number 4 includes both kimberlites and ultramafic lamprophyres (melilitites and or aillikites). The Torngat dikes are affiliated with the Abloviak shear zone and several are diamondiferous (Wilton and others, 2002).

Manitoba

Exploration in Manitoba resulted in discovery of the Wekusko kimberlite dike north of Lake Winnipeg. Research by the Canadian Geological Survey resulted in the identification of numerous indicator mineral trains in the Gods Lake-Knee Lake area near the Snow Lake-Flin Flon area. The indicator mineral trains suggest the presence of several hidden, mantle-derived pipes in eastern Manitoba.

Northwest Territories (NWT) – Nunavut

Diamond deposits have been discovered at numerous locations in the Canadian far north. Some of the more important are: (1) Lac De Gras (NWT & Nunavut), (2) Thirsty Lake (Nunavut), (3) Parry Peninsula (Darnley Bay) (NWT), (4) Victoria Island cluster (NWT- Nunavut), (5) Somerset Island cluster (Nunavut), (6) Rankin Inlet cluster (Nunavut), (7) The Melville Peninsula (Nunavut), (8) Baffin Island (Nunavut), (9) Dry Bones Bay (NWT) and (10) Coronation Bay (Nunavut).

(1) *Lac De Gras region*

A major kimberlite district was discovered in the Slave Province northeast of Yellowknife in the Northwest Territories in the early 1990s. Several commercial pipes and sill have been identified in this region that include the Ekati group, Diavik group, Snap Lake, Gahcho Kue (formerly Kennady Lake) and Jericho (fig. 8). There are many other kimberlites in this region such as those at Carp Lake, Hardy Lake and others, but only the commercial deposits are described.

Figure 8. Northwest and Nunavut diamond mine localities.

One of the great exploration success stories in history was the discovery of diamonds in the Canadian Northwest Territories, which sparked the largest claim staking rush in history (Krajick, 2000). Within a few years, capitalization of the *Ekati mine* resulted in the first Canadian diamond mine. Production began in 1998. Since mine operations started, other commercial properties have been identified that include the Snap Lake dike and the Diavik pipes. A fourth commercial diamond prospect in Canada, *Jericho*, is located in Nunavut 100 miles (160 km) north of Ekati and 250 miles (400 km) NNE of Yellowknife. Of these four commercial operations Ekati is by far the largest operation. Most kimberlites in the Northwest Territories were emplaced at 45 to 75 Ma (Simandl and others, 2005).

Ekati kimberlites. The kimberlites at Ekati are located nearly 180 miles NE of the town of Yellowknife. Several pipes were discovered lying under a group of shallow lakes in the Lac de Gras region in the early 1990s. A short time following the discovery, Canada's first diamond mine was commissioned by BHP in late 1998. This world-class mine includes a cluster of 121 kimberlite intrusives (52 to 65 Ma) and reserves established for the Fox, Leslie, Misery, Koala, Koala North, Panda, Beartooth, Sable and Pigeon kimberlite pipes on the Ekati property: other kimberlites are being evaluated and the mine has an anticipated minimum life of 25 years.

In 2001, three years after the mine opened, the Ekati produced 3.7 million carats. In 2003, production increased to 6.96 million carats (EMJ, 2004). Open pit operations on the Panda pipe reached maximum economic depth in 2003, five years after mining was initiated. Declining production from the Panda open pit has been replaced by production from the nearby

Misery and Koala open pits. The Panda mine life will be extended by underground mining, and the kimberlite is being developed by sublevel retreat mining. Underground mining was previously initiated at the adjacent Koala North pipe in 2002. The Panda underground mine is expected to produce 4.7 million carats over an operating period of 6 years: production was scheduled in 2005 followed by full production in 2006. Ekati production for the first quarter of 2004 totaled 1.27 million carats, which was a 40 percent decline from the previous quarter. For the first 9 months of fiscal year 2004, the Ekati mine produced more than 5.3 million carats.

On June 30th, 2003, it was reported that the Ekati mine had 47.7 million tonnes of reserves averaging 80 cpht (36.6 million carats of recoverable diamonds) based on a 2 mm cutoff size (the size that distinguishes macrodiamonds from microdiamonds is 2 mm, although some companies use a 1 mm diameter cutoff size). Measured, indicated, and inferred kimberlite resources stood at 127.9 million tonnes of ore with an estimated 171.2 million carats (Robertson, 2004)! As exploration continues on the property, reserves should increase (Hausel, 2006).

The Panda kimberlite is small, steeply-dipping carat-shaped pipe that is 640 feet (195 m) across and roughly circular in plan covering a surface area of only 7.4 acres (3 ha). The fault-controlled pipe is slightly asymmetrical in vertical section. Panda has been delineated to depths of 1,800 feet where it tapers to a narrow 64-foot-wide blow. The structure is filled with a complex mixture of volcaniclastic kimberlite containing variably carbonized wood fragments and mudstone that are locally abundant in bedded material at depth. Primary diatreme-facies kimberlite is present in the lower portions of Panda (more than 1,150 feet below surface) and minor intrusions of hypabyssal-facies kimberlite occur as occasional narrow peripheral dikes (McElroy and others, 2003).

The Misery Main pipe is an even smaller intrusive of only 3.7 acres (1.4 ha). It is elongated and steep-sided with dimensions of 295 by 574 feet at the surface. According to Mustafa and others (2003), the pipe transects a contact zone between Archean granite and metagreywacke with its location corresponding to the intersection of this contact with a narrow, N-S trending shear. The Misery Main pipe ranges from ash- to mud-rich phases to coarse-grained, olivine-rich volcaniclastic kimberlite. In places, fine-scale bedding is defined by abundance variations and grain size of olivine. Numerous other kimberlite intrusives occur in the immediate vicinity of the Misery Main kimberlite. The Misery Main pipe is largest in this local cluster while the others include narrow hypabyssal dikes that radiate out from the pipe, pipe-like hypabyssal intrusions, and small pipes with diatreme-facies kimberlite (Mustafa and others, 2003).

Diavik mine. Production at the Diavik mine began in 2003. The Diavik pipes are located west of Ekati and are operated by Diavik Diamond Mines: a joint venture between Rio Tinto (60 percent) and Aber Mines (40 percent). Rio Tinto assumed responsibility from their subsidiary Kennecott Canada Exploration. Fifty-five kimberlites occur on the Diavik property of which 25 are diamondiferous and at least four are commercially mineralized. The mine is estimated to contain 138 million carats in four kimberlites (A154S, A154N, A418, A21). Of these, the A154S kimberlite is one of the richest in the world with a reserve of 11.7 million carats at an average grade of 520 cpht.

Operations currently focus on the A154S and A154N, with production scheduled to reach 6 to 8 million carats/year. The mine has resources to sustain an operation for 16 to 22 years. In 2004, the mine produced 7.6 million carats including some large stones that weighed up to 151 carats. The property lies on a 7.7 mi^2 island known as East Island located 180 miles NE of Yellowknife. The Diavik kimberlites (55 Ma) intrude the Precambrian Slave basement complex (2.5 to 2.7 Ga) and several underlie lakes. Capitalization to initially open the mine were on the order of $1.3 billion, but the mine made up for high capitalization by surpassing the 20,000,000 carat production mark at the end of 2005!

Snap Lake mine. This mine is scheduled to begin diamond recovery from a kimberlite sill 60 miles SSE of Ekati and 130 miles NE of Yellowknife. The sill dips under adjacent Snap Lake and has a strike length of 2 miles and 15o dip with dip length of at least 1.9 miles. DeBeers began mine construction in 2006 and anticipates full production in 2008. The ore will be mined entirely underground from rock estimated to contain 38.8 million carats in 22.8 million tonnes (146 cpht) (Robertson, 2004). The mine life is anticipated for 22 years. Snap Lake is one of three properties under developed by DeBeers. The other two are Gahcho Kue east of Snap Lake and Victor in the James Bay Lowlands of northern Ontario.

Gahcho Kue (formerly Kennady Lake) mine. The Gahcho Kue property lies south of Lac de Gras, 50 miles SE of Snap Lake near Ft. Defiance and 186 miles NE of Yellowknife. At least 8 diamondiferous kimberlites lie on this property including sills and dikes. Inferred and indicated resources for three pipes are 31.4 million carats averaging 148 cpht with reserves averaging 167 cpht. Estimates suggest a potential tonnage of at least 20 million tonnes of ore in the 5034, Hearne and Tuzo pipes. Gahcho Kue is being developed by joint venture (Mountain Lake Resources and DeBeers) (EMJ, 2004). The mine is anticipated to have a life of 15 years and produce 3 million carats annually when in full production.

Jericho mine. The Jericho mine includes six diamondiferous kimberlites. During bulk sampling of one pipe by Tahera Exploration, a decline was driven to obtain a 9,435 tonne bulk sample which yielded 10,539 carats at a cutoff size of 1 mm. The stones included 44 diamonds between 5 and 10 carats and 23 stones greater than 10 carats: the largest weighed 40 carats. Production at Jericho began in January of 2006. The mine lies south of Carat Lake within the Nunavut Territory 260 miles NE of Yellowknife, about 106 miles north of the Ekati mine near Echo Bay's Lupin gold mine. The principal Jericho kimberlite (172 Ma) is a multiphase intrusive measuring 960 by 120 feet and is on dry land. The pipe has an indicated and inferred resource of 7.1 million tonnes averaging 84 cpht with an estimated resource of 6 million carats that will be recovered over 9 years. Reserves of 2.6 million tonnes at 120 cpht have been established (EMJ, 2004).

About 8 miles west of Jericho is the Muskox pipe. This kimberlite has twice the surface area as the Jericho pipe and may considerably extend the life of the Jericho mine. Bulk samples from the Muskox pipe have yielded grades from 26 cpht to 142 cpht (Northern Miner, 2006, 92:6, p 1-2).

(2) Thirsty Lake lamprophyre

The Thirsty Lake dike is part of the Akluilak dike system in the central Churchill Province of the Northwest Territories along the northwestern margin of Hudson Bay. The dike system lies west of the Rankin Inlet kimberlites. Kaminsky and others (1998) interpret the dike as a metaminette. Similar to some ultrahigh pressure metamorphosed diamond deposits in the Kazakhstan region, this deposit is very rich in microdiamonds (Hausel, 1996; Erlich and Hausel, 2002). A small 44 pound sample collected from the dike yielded more than 1,700 diamonds, but the sample lacked macrodiamonds (MacRae and others, 1995).

The Thirsty Lake North and South dikes comprise a zone with a strike length of more than 9 miles. Diamonds recovered from the property are strongly colored yellow and brown diamonds with cubo-octahedral and cubic forms and lesser dodecahedral habits. Nitrogen aggregations of the diamonds are comparable to those of the Kokchetav massif diamonds in

Kazakhstan (Chinn and others, 2000). The Kokchetav diamonds are believed to have formed during an ultrahigh metamorphic event (DeCorte and others, 1998; Erlich and Hausel, 2002). A similar event is not recognized at Thirsty Lake.

The chemistry of mineral inclusions in the microdiamonds suggests the Thirsty Lake stones grew metastably within the graphite-stability field similar to those in Kazakhstan. According to Chinn and others (2000), the diamonds exhibit elevated hydrogen which has been connected to nucleation processes for synthetic diamonds. The presence of the high volatiles (H and N) associated with these diamonds may have been responsible for metastable growth of microdiamonds at pressures below the diamond-stability field. The high hydrogen abundance is thought to explain the high nucleation rate for microdiamonds and the lack of macrodiamonds in this deposit (Chinn and others, 2000).

(3) Parry Peninsula

Along the Parry Peninsula to the NNW of Ekati, adjacent to Darnley Bay in the Amundsen Gulf north of the Arctic Circle, exploration was initiated over the strongest isolated gravity anomaly in North America in a search for ultramafic-hosted nickel and platinum-group mineralization. During exploration in 1997, an aeromagnetic survey flown over the anomaly identified several characteristic "bulls-eye" mag-anomalies typically associated with diatremes. Many of these were evaluated and 12 were drilled resulting in the discovery of kimberlite (270 Ma) at 10 anomalies: diamonds were recovered from 6 of the intrusives.

(4) Victoria Island cluster (Nunavut)

The Victoria Island cluster lies east of the Parry Peninsula and a considerable distance north of Yellowknife. The Snowy Owl kimberlite within this cluster consists of hypabyssal-, diatreme- and crater-facies kimberlite. Initial samples (966 lbs) yielded 785 microdiamonds with 4 macrodiamonds. The nearby Longspur kimberlite yielded 36 microdiamonds and 3 macrodiamonds from a 198-lb sample, and the Golden Plover kimberlite yielded 41 microdiamonds and 3 macrodiamonds from a 397-lb sample of crater and hypabyssal facies kimberlite.

(5) Somerset Island cluster (Nunavut)

The Somerset Island cluster (Nunavut) is located 200 miles east of Victoria Island within the Arctic Circle. A cluster of 36 kimberlites on Somerset Island show strong NE-, NW- and also N-S structural controls that parallel basement foliation. A few kimberlites (88 to 105 Ma) appear to be weakly mineralized with microdiamonds. The Somerset Island kimberlites lie to the west of the Brodeur Peninsula kimberlites along the NW extent of Baffin Island. Diapros established a 1-ton/hr processing facility in the vicinity of the Batty kimberlites in the summer of l972 and processed 262.3 tons of kimberlite. An additional 215.1 tonnes were processed from the Diapron, Batty, Nord, Oucat, Ham and Elwin kimberlites. Diamonds were recovered from Nord.

The kimberlites have hypabyssal and diatreme facies (105 Ma). The transition from lithosphere to asthenosphere at depths of 87 miles beneath Somerset Island is suggested. The presence of diamonds indicates that the kimberlites tapped the lithosphere within the diamond stability field, although the lithospheric root is believed to be thinner under Somerset Island than in the central Slave craton.

Other notable diamondiferous occurrences are located within the Nunavut Territory. Exploration continues in the Tomgas region of southeastern Nunavut and the north coast of Baffin Island. Further to the southeast, the Torngat dikes (346 Ma) are analogous to the kimberlite dikes of west Greenland. The extent of Proterozoic metasomatism within the lithosphere beneath the western Churchill Province is still poorly documented and its effects on diamond stability are not understood (Armstrong, 2000).

(6) Rankin Inlet

Much of this region is underlain by the Churchill Province. These kimberlites were emplaced in the Archean Rankin Inlet group of metamorphics. The kimberlites lie about 75 miles ESE of the Thirsty Lake (Parker Lake) diamondiferous minette dike that is believed to be associated with the magmatic event responsible for the Christopher Island Formation (Proterozoic). Past exploration in the region was largely for gold and base metals and systematic exploration for diamonds has been limited. Some kimberlite dikes (192-214Ma) were intersected during drilling at the Meliadine gold deposit. In 2003, Cumberland and Comaplex announced the discovery of 11 new kimberlites, and the Geological Survey of Canada reported numerous kimberlite float occurrences along the Meliadine trend. These provide evidence for multiple kimberlitic sources in the Churchill region.

Exploration resulted in the recovery of 145 KIMs from 183 till samples. About 46 percent of the pyropes were G10 (garnets that are chemically similar to diamond-inclusion garnets) subcalcic pyropes (Gurney, 1984). The indicator mineral results define several corridors of interest on the property that were followed up in 2003 with more than 1,800 till samples and a high resolution airborne magnetic survey identified 226 priority targets. In 2003 a follow-up line identified more than 100 additional high priority targets including a cluster of 29 magnetic lows. The geophysical evidence suggests that a kimberlite cluster of more than 100 pipes may be present at the Churchill property!

Ground geophysics completed on 58 targets resulted in 29 being selected to drill and resulted in discovery of 16 kimberlite pipes. This cluster occurs over a spatially large area measuring 37 by 30 miles. The kimberlites were initially recognized as magnetic highs and lows with some correlating EM signatures. Nine kimberlites yielded diamonds (Strand, 2004).

(7) Melville Peninsula

The Melville Peninsula is located along the edge of the RAE craton, north of the Arctic Circle adjacent to the Foxe Basin and south of Baffin Island. A group of 9 diamondiferous kimberlites known as the Aviat kimberlites were discovered in this region as well as till samples with diamond-stability (G10) pyrope garnets. These kimberlites lie NE of another group of kimberlites referred to as the Wales Island kimberlites. Based on a 10.4 tonne sample, the AV-1 kimberlite yielded a preliminary ore grade of 83 cpht. The Wales Island kimberlites to the southwest include a group of 10 kimberlites.

(8) Baffin Island

Results from an aeromagnetic survey led to the staking of approximately 75,000 acres in the south central region of Baffin Island. One of the three claim blocks contains 14 discrete geophysical anomalies that vary in size from 410 to 2,625 feet in diameter. All of the anomalies are within a single cluster and in an area considered to be structurally favorable for kimberlite intrusion.

The Jackson Inlet kimberlite on the West Coast of the Brodeur Peninsula of Baffin Island is centered 2 miles south of Jackson River. The Brodeur Peninsula is bounded by Admiralty Inlet, Lancaster Sound and Prince Regent Inlet. Flat-lying Ordovician and Silurian carbonates are exposed along the steep coastline of the Brodeur Peninsula and in the deeply incised river gorges. Between these gorges, the land surface forms an undulating plateau. Except at the crests of some hills, a thick blanket of glacial till was deposited by a small ice cap centered on the peninsula during the last glaciation and beyond the northern limit of the continental glacier which covered much of Canada.

Although isolated gneissic erratics provide evidence of earlier more extensive glaciation, the till consists mainly of carbonate blocks in a matrix of pulverized carbonate that supports very sparse vegetation. From the air and on aerial photographs, evidence of the Jackson Inlet cluster of kimberlites is manifested as three dark brown circular patches within a 1,640 by 1,970 foot halo of tan coloration. Within the halo are patches of darker tan color. The surrounding Ordovician-Silurian limestone is grey and the tan color of the halo is interpreted as a result of limestone weathering, which was dolomitized by introduction of magnesium from the kimberlitic magma.

(9) Drybones Bay kimberlites (NWT)

At least 3 diamondiferous kimberlites have been found in the Drybones Bay area along the north shore of the Great Slave Lake to the east of Yellowknife.

(10) Coronation Gulf

The Coronation Gulf area, located 70 miles NNW of the Jericho mine, includes a group of more than 11 diamondiferous kimberlites. The Knife Pipe, under exploration by DeBeers, is described as being significantly diamondiferous. Ashton Mining reported highly encouraging results from caustic fusion analyses of kimberlite from their nearby Potentilla, Stellaria and Artemesia pipes. Samples of the Potentilla kimberlite include hypabyssal and diatreme facies with an estimated grade of 17.5 cpht.

Ontario

North of the Great Lakes in Ontario, a number of kimberlites, some lamprophyres, and a group of diamondiferous actinolite schists are recognized. To date, the most notable appear to be the Attawapiskat cluster and the Wawa dikes. Other discoveries in Ontario include kimberlites at Kyle Lake, Kirkland Lake, Keith Township, New Liskeard and others. Only the principal occurrences are described: (1) The *Attawapiskat cluster* includes several well-mineralized kimberlites including the Victor pipe in the tundra near Hudson Bay; (2) The *Kyle Lake kimberlite cluster* about 60 miles west of the Attawapiskat cluster; (3) The *Kirkland Lake cluster* along the eastern Ontario border adjacent to Quebec, and unconventional host rocks of great interest known as (4) the *Wawa cluster* on the northeastern shore of Lake Superior.

(1) Attwapiskat cluster

The Attwapiskat cluster includes 20 kimberlites (155 to 170 Ma) near the Attwapiskat River in the James Bay lowlands along a distinct NNW trend. One commercial pipe has been identified within this field. The project, operated by DeBeers, encloses 18 kimberlite pipes, 16 of which are diamondiferous. The Victor Main and Victor Southwest pipes are two pipes that coalesce at the surface and have a combined area of 37 acres. The composite pipe is formed of pyroclastic crater, diatreme and hypabyssal facies kimberlite with highly variable diamond grades. The pipe averages 33 cpht with an average value of $154/carat. Plans are to develop an open pit with an expected 12-year mine-life and total project life of 17 years. The Victor mine would be supported by a plant with a designed capacity of 2.5 million tonnes/year.

In 2003 and 2004, airborne magnetic signatures were evaluated within the Attwapiskat cluster and 5 previously unknown kimberlite pipes were found in the MacFayden group. The interpretation of the magnetic total field showed distinct circular magnetic isograds along a prominent NNW magnetic trend interpreted as a buried kimberlite dike. This trend continues for about 11 miles or more. This group is situated along the bank of the Attwapiskat River. The Victor pipe, 5 miles to the SSE, lies along the same trend.

(2) Kyle Lake

The Kyle Lake kimberlite cluster, 60 miles west of the Victor pipe, includes a group of 5 Precambrian kimberlites. Preliminary tests of the Kyle Lake #1 kimberlite yielded an average grade of 60 cpht. Several phases were mapped in the kimberlite including one that yielded an ore grade as high as 800 cpht! The surface area of the kimberlite is only 6.2 acres, but it has an ore resource of 14.5 million tonnes to a depth of 1,670 feet. The recovered diamonds show little resorption and have distinct octahedral habit. The Kyle Lake #3 kimberlite lies near the confluence of the Attwapiskat and Muketei rivers. This is a vertical dike with average width of 82 feet and a blow at one end that increases the width to 410 feet. The dike has been traced to more than 1475 feet along strike, and has an even greater strike length based on ground magnetic surveys. The average grade based on limited sampling was 92 cpht.

(3) Kirkland Lake

The Kirkland Lake group includes two clusters within the Kirkland Lake mining district. The Kirkland Lake district is a well-established gold mining camp underlain by Archean rocks (2.5 to 2.7 Ga) of the Superior Province. Proterozoic rocks of the southern Cobalt Group of the Huron Supergroup (2.5 to 2.2 Ga), Grenville Province metamorphics (1.1 Ga) and Phanerozoic sedimentary rocks also underlie the region. The Kirkland Lake kimberlites (150-159 Ma) include a cluster of 10 pipes in the Kirkland Lake area as well as to the south near Cobalt in the New Liskeard area near Lake Timiskaming, along with 11 dikes in the Kirkland Lake area. Some of these are weakly mineralized and the geochemistry supports that the kimberlites should only be weakly mineralized. The kimberlites in the New Liskeard area continue from Ontario into Quebec along a northeasterly trend (Schulze, 1996).

(4) Wawa cluster

The Wawa deposits are similar to deposits in the Akwatia field, Ghana. The Wawa discovery is significant: these are the oldest diamond deposits ever found and they occur as stratiform, metamorphosed schists within an Archean greenstone belt. The host rock precursors remain an enigma, and have been interpreted as metamorphosed lamprophyre, metamorphosed crater facies kimberlite, lahar, breccia, conglomerate and even komatiite. It may be some time before the origin of these hosts is known. At any rate, the discovery provides a whole new concept in exploration for diamonds worldwide.

The host rocks are Archean (2.7 Ga) diamondiferous ultramafic breccias and schists. Limited sampling of some breccias yielded grades ranging from 6 to 262 cpht (Wilson, 2004). The largest diamond found to date is 1.39 carats.

The deposits occur within the western Michipicoten greenstone belt of the Wawa subprovince of the Superior craton and have been metamorphosed and deformed during 4 episodes of deformation with little evidence of their precursor being preserved. Two types of diamond-bearing rocks are described: both have been metamorphosed to upper greenschist facies and are described as a younger lamprophyre(?) and a volcaniclastic breccia. Both the lamprophyre and breccia are intercalated with 2.7 Ga felsic to intermediate metavolcanics, intermediate to mafic metavolcanics and mafic intrusive rocks.

The matrix- to clast-supported breccia forms about 200- to 230-foot-thick units. It contains dominantly angular, granular to large boulder-sized fragments with a wide variety of igneous lithologies including metamorphosed ultramafic rocks with high Cr and Ni. The breccias are interpreted as volcaniclastic debris flows based on stratigraphy, the wide range in fragment lithologies, crude bedding, poor sorting, and lack of sedimentary structures. The fine-grained breccia matrix is comprised of upper greenschist to epidote-amphibolite mineral assemblages, which includes 50-75 percent actinolite, 1-20 percent epidote, 1-20 percent titanite 1-10 percent quartz/feldspar, 0-20 percent biotite, 0.5-15 percent hornblende, and 0-10 percent chlorite, with minor calcite, albite, opaques and rutile.

The rock may occur as dikes that appear to cross-cut the metavolcanic sequences and breccia. In some areas the relationship between the lamprophyre(?) and breccia, and the lamprophyre(?) and metavolcanics is unclear. The lamprophyre overlies these rocks along straight, long, parallel contacts that may be depositional in origin with 5-10 percent fragments of surrounding country rock, occasional altered ultramafic mantle xenoliths, and rare breccia. The lamprophyre is weakly foliated as defined by faint alignment of actinolite and biotite grains.

Whole rock compositions of breccia matrix, juvenile clasts and lamprophyre show no major systematic differences between compositions of the breccia, its juvenile clasts and the lamprophyre. This may be interpreted as a complete obliteration of primary magmatic compositions by metamorphism, or as a reflection of similar compositions of the protoliths. The rocks are alkaline to sub-alkaline based on (Na2O + K2O) vs. SiO2. Major element compositions show a better fit to calc-alkaline lamprophyre and lamproite of Rock (1987, 1991).

Bulk rock compositions cannot be used since the rocks are hybrids with incorporated mantle xenoliths. They may have experienced additional compositional changes during metamorphism. Some phenocrysts may provide clues. Hornblende phenocrysts retain relict magmatic compositions as they display concentric oscillatory zoning rarely found in metamorphic rocks. Assuming that Mg-hornblende, tschermakite, edenite and pargasite retained original magmatic compositions, their protoliths could be similar to calc-alkaline lamprophyre. The hornblende compositions are not compatible with orangeites (kimberlites) and lamproites; the latter containing Ti- and K- richterites. Hornblende the Wawa lamprophyre and volcaniclastic breccia could have crystallized from calc-alkaline lamprophyre.

Diamonds are found in both breccia and lamprophyres. Both have metamorphosed ultramafic mantle xenoliths. The presence of these xenoliths and diamonds is evidence for preservation and incorporation of mantle material into the lamprophyric magma. The diamond population from the polymictic volcaniclastic breccia is dominated by microdiamonds. The majority of macrodiamonds are colorless, have non-uniform color, or are yellow and show very little resorption and are dominated by pristine octahedrons. They form single crystals and aggregates with predominant octahedral and occasional cubic morphology. Many diamonds have experienced breakage and late etching (Lefebvre and others, 2003). Of the microdiamonds, some colored stones suggest possibilities for fancy stones including pink, rose, amber, green, yellow and brown (White-Kirkpatrick, 2003).

The two types of diamondiferous rocks from Wawa have been interpreted as metamorphosed polymictic volcaniclastic breccia and lamprophyre based on field observations, petrographic studies, and mineral chemistry. The matrix of the breccia, the juvenile material and the lamprophyre have similar mineral assemblages, bulk rock compositions and mineral chemistry which suggests they may have formed from a similar type of magma. This primary magma was likely to have had calc-alkaline affinity based on the chemistry of hornblende. The magma must have originated with the diamond stability field, as it incorporated diamond-bearing mantle material upon ascent to the surface. It erupted during the Archean to produce volcaniclastic deposits and later was intruded as dikes. A highly explosive eruption style that produces volcaniclastic rocks is not characteristic of lamprophyric magmas that commonly intrude as dikes. Thus, the Wawa diamondiferous rocks could be one of few known lamprophyric volcanoes (Lefebvre and others, 2003).

Similar examples have been described in Namibia, New Mexico and southern Alberta. The Wawa lamprophyres belong to a greenstone belt volcanic sequence and formed in a subduction-related tectonic setting. The presence of diamond in subduction-related magmatic rocks suggest that diamonds may have already formed at earlier stages of subduction, well before later incorporation in subcratonic eclogites. Thus, similar rocks in similar geological environments should be considered as potential targets for diamond exploration (Lefebvre and others, 2003). During the mapping and sampling of Wyoming's greenstone belts in the past, the search for similar lamprophyres as well as diamondiferous komatiites was not considered at Elmers Rock (Graff and others, 1982), Rattlesnake Hills (Hausel, 1996), Seminoe Mountains (Hausel, 1994) or South Pass (Hausel, 1991).

The Wawa deposits have similarities to diamondiferous metakomatiites described in the Akwatia diamond field within Birimian (Early Proterozoic), where kimberlitic indicator minerals were lacking. In the Akwatia field, the diamond deposits represent some of the oldest diamond deposits that have been found, and the rocks occur in arc sediments not associated with an Archon. The diamondiferous rocks are actinolite/ tremolite schists and actinolite rocks with little or no schistocity and distinctive clastic texture with clasts of phyllite and carbon. The clastic units are elongate and contained within the actinolite schist. Major and trace element analysis of these rocks suggest a suite of rocks similar to the diamond-bearing volcaniclastic komatiites of French Guiana and/or the metamorphosed suit of komatiite/ boninite type rocks of the Wawa (Superior Province) greenstone belts (Canales and Norman, 2003).

Quebec

Diamond has been found in both kimberlite and in some unconventional host rocks in Quebec: both kimberlites and ultramafic lamprophyres have been discovered. Some deposits include: (1) *Torngat district,* which encloses the Abloviak kimberlites and/or lamprophyres along the edge of Ungava Bay in extreme northern Quebec, the (2) *Wemindji kimberlite* on the shoreline of Hudson Bay, (3) *Otish Mountains district* (Renard and Indicator Lake kimberlites) in central Quebec, (4) the *Desmaraisville kimberlite field* (5) the *New Liskeard* cluster on the western border of Quebec north of Sudbury, and (6) an unconventional host (alnöite) *at Ile Bizard* near the U.S. border along the St. Lawrence River east of Ottawa (Erlich and Hausel, 2002; DeBeers, 2003).

(1) Torngat district

The Torngat district lies adjacent to the Ungava Bay region in Quebec. It consists of a group of olivine-rich hypabyssal facies rock (550 Ma) known as the Abloviak dikes that intrude Paleo-Proterozoic paragneiss and metasedimentary rock along the Abloviak shear zone. The dikes are 6.5 feet wide and have been traced from a few feet to more than 1.8 miles along strike. They were emplaced in brittle fractures that cut foliation and mineralogically consist of anhedral olivine, pyrope, phlogopite and ilmenite macrocrysts in fine-grained phlogopite, olivine, spinel and carbonate matrix. Pyrope compositions match calcic pyrope-almandine, calcic chromian pyrope, and subcalcic chromian pyrope. Rock compositions have high K2O/Na2O, high Mg#, low SiO2, low Al2O3 and elevated TiO2 suggesting affinity to aillikitic lamprophyre or Group I kimberlite.

In addition to the Abloviak dikes, the kimberlite and aillikite dike swarms in the Holsteinsborg, Safartoq and Sukkertoppen regions of Greenland are thought to be an extension of the Abloviak dike complex. The age and geological setting of the Greenland and Quebec dikes suggest similar genesis (Digonnet and others, undated). Some high-quality diamonds were recovered from low grade ore in the complex (Cumming, 2006).

(2) Wemindji kimberlite

Kimberlite was discovered near Wemindji in the Quebec lowlands on the east shore of James Bay in early 2002. The Wemindji area lies at a junction of two major Proterozoic structures; the Wemindji-Caniapiscau corridor and the NE extension of the Kapuskasing structural zone. The basement rocks are Archean (2.8 Ga) and part of the Superior Craton with remnants of a Mesoarchean Craton.

Kimberlite was discovered by drilling at the head of a 1.2 mile long KIM dispersion train. The hole intersected sub-horizontal 6.4 foot thick kimberlite at depths of 12.8 to 105 feet. The geometry suggests a shallow-dipping folded and faulted sill or stacked sills. Indicator minerals are dominated by abundant picroilmenite, secondary garnet, and uncommon chromite and chrome diopside. Mineral compositions indicate that ilmenites and approximately 50 percent of garnets and clinopyroxenes from samples of the Wemindji pipe are megacrysts. The remaining garnets are predominantly lherzolitic with subordinate wehrlitic population and rare harzburgitic grains. Only a very small proportion of the clinopyroxenes recovered were derived from garnet lherzolite (Letendre and others, 2003).

(3) Otish Mountains district

The Superior Craton hosts a variety of mantle-derived rocks that include kimberlite and ultramafic lamprophyre of varying compositions (Birkett and others, 2003). To date, several pipes, some sills, and several geophysical anomalies typical of hidden diatremes have been found in the Otish Mountains district. Many of the intrusives were tested with poor results, with one exception: the Renard intrusives on the Foxtrot property in LaBelle Province east of James Bay. The Renard intrusives yielded one 459-carat parcel of diamonds from a 664-tonne sample collected from four intrusives. The largest diamond weighed 4.3 carats (Cumming, 2006). At least 11 intrusives have been identified in this cluster. Small bulk sample tests have yielded grades of 134 cpht for the Renard 3 to 65 cpht for the Renard 2.

The host rocks may be kimberlite; however, preliminary mineralogical and geochemical tests suggest these rocks have melnoite affinities. In spite of the high temperatures of emplacement and significant incorporation of country rock into the host rocks, some Renard intrusives potentially have commercial grades and diamonds of commercial size (Birkett and others, 2003).

Kimberlitic and lamprophyric intrusives of the Renard, Tichégami River and Beaver Lake areas lie at the southern end of the Mistassini-Lemoyne structural zone. This zone extends over 405 miles NNE of the Mistassini Basin to the Labrador Trough, in the Cambrian Lake region and possibly into the Lemoyne Lake region. From south to north it includes the Beaver Lake kimberlites (551 Ma), the Tichégami River intrusives, the Renard region, the Archean Niaux nepheline syenite suite and Proterozoic Castignon Lake (1.88 Ga) and LeMoyne carbonatites (less than 1.87 Ga) of the Labrador Trough (Moorhead and Houle, 2002).

(4) Desmaraisville kimberlite field (Bachelor Lake)

The area west of Matagami, in the northwestern part of the Archean Abitibi greenstone belt, became a target for diamond exploration in Québec following discovery of KIMs in glacial debris. The surface textures of several grains suggested a proximal kimberlite source. The first discovery of dikes of kimberlite in the Abitibi greenstone belt occurred in 1955 in the

Desmaraisville area, in the north-central part of the subprovince, during exploration for gold. In 1992, a diamond-bearing kimberlite pipe was found in the same region. The Desmaraisville kimberlite field contains 5 weakly diamondiferous hypabyssal pipes and several dikes. It is located in the Waswanipi-Saguenay structural zone, which forms the NW-extension of the Saguenay Rift (Doucet, 2002).

(5) New Liskeard kimberlite

The New Liskeard kimberlite cluster is located near the Temiskaming Structural Zone. This structure controlled the emplacement of the Victor pipe in the James Bay Lowlands and is the controlling element to more than 20 kimberlites in the New Liskeard area including diamondiferous kimberlites known as 95-2, KL-1 and KL-22 in Lundy and Klock Township west of New Liskeard.

(6) Ile Bizard

The Ile Bizard intrusion is one of several diatremes within the Oka carbonatite complex west of Montreal. In the 1960s, a sample from the diatreme yielded 10 microdiamonds, although there was concern of possible contamination in the diamond mill in Johannesburg. It is not known if the diatreme has been resampled. The host rock has been described as alnöite, although work by Raeside and Helmstaedt (1982) suggest that the intrusive lacks characteristics of alnöite and may best be classified as a lamprophyre until further work can be completed.

Saskachewan

A major kimberlite district known as Fort a la Corne was discovered near the town of Smeaton. This district has attracted considerable attention due to the number of kimberlites and the large size of the intrusives. The Fort a la Corne project, 30 miles NE of Prince Albert includes more than 70 large kimberlites ranging in area from 6 to 318 acres that typically lie under 320 feet of glacial cover (Robertson, 2004). The kimberlites are thought to have laterally extensive sub-horizontal lenses of crater facies kimberlite that are as much as 6,400 feet in diameter and in some cases are as much as 320 feet thick. Kimberlites were discovered in this region by follow-up drilling projects into circular to sub-circular complex magnetic anomalies.

The Fort à la Corne kimberlite field consists of Cretaceous volcaniclastic-dominated crater-facies kimberlites that are highly variable in size, complexity and diamond content. They vary from small simple to large, very complex, multi-phase kimberlites with as many as 6 eruptive phases. Furthermore, each eruptive phase may have various sub-facies. The largest kimberlite has about 675 million tonnes and is comparable to the largest kimberlites in the world. Since their initial discovery in 1988, over 75 percent of the kimberlites have proven to be diamondiferous; approximately 50 percent have yielded macrodiamonds (Harvey, 2004).

The Fort à la Corne field is one of the largest in the world and consists of two clusters along with many isolated intrusives. The main Fort à la Corne cluster forms a NNW-trending 22 mile long trend that is 6 miles wide. Surrounding the main cluster, the Snowden cluster to the NE is aligned along a NNW-trend with the Foxford and Birchbark kimberlites further NW, the Weirdale kimberlites to the west and the Candle Lake kimberlites to the north. In total, over 75 percent of kimberlites in the Fort à la Corne field have been verified as diamondiferous. Close to 70 percent of recovered macrodiamonds are gem quality (Harvey, 2004).

Yukon

Exploration in Yukon by Patrician Diamonds reports discovery of KIMs with some diamonds in an undisclosed drainage. Reported lamprophyres of kimberlitic affinity may lead to some additional exploration in the Yukon as well as Alaska.

Some rocks of interest include the Early Cambrian Quartet Mountain lamprophyres. These are ultramafic alkaline dikes emplaced in the Wernecke and Mackenzie Mountains supergroups in the Wernecke Mountains of northern Yukon. The Quartet Mountain lamprophyres are porphyritic with phenocrysts of phlogopite ± diopside ± olivine in dark-gray aphanitic groundmass and are suggested to have arisen from depths of more than 56 miles. One lamprophyre has abundant olivine xenocrysts pseudomorphs along with crustal and mantle xenoliths. The dike resembles kimberlite due to abundance of mantle xenoliths and xenocrysts but differs from kimberlite in abundance of phlogopite phenocrysts. It has been described as an ultramafic lamprophyre of kimberlitic affinity.

Many other deposits have been found in Canada since the 1990s in the Northwest Territories, Nunavut, Alberta, Ontario, Quebec, and Saskatchewan (Olson, 2001). According to EMJ (2004), Canada is currently supplying about 15 percent of the world's diamonds and is expected to show dramatic production increases in the future. In 2002, the Canadian diamond industry produced nearly 5 million carats. In 2003, production increased to 11.2 million carats, and it is estimated that essentially 50 percent of the world diamond exploration funding is focused on Canada.

In addition to the commercial properties, many other successes have been made. DeBeers alone reported the discovery of more than 219 kimberlites in 12 different regions of Canada, of which more than half are diamondiferous. Typically, only one in every 200 kimberlites will contain sufficient numbers of diamond of high enough value to open a commercial mine (Hausel, 2006).

CONCLUSIONS

With the current trend of investment, exploration, and progressive pro-mining atmosphere, it is anticipated that Canada will be a leading diamond producer for decades to come. The sheer size of the North American Craton allows one to predict Canada to become the world's number 2 source for diamonds in the very near future. Unless there is a major change in attitude in the U.S., little is expected to be produced, even though parts of the U.S. (i.e., Superior and Wyoming Provinces) are underlain by favorable terrain for gemstones.

Exploration investment in the search for diamonds in Canada amounts in the hundreds of millions to billions of dollars. Exploration and research investment in the search for diamonds in the U.S. is more on the order of hundreds of thousands of dollars spent over the past few years. With such poor investment by various state governments, U.S. will continue to lag behind Canada in major diamond discoveries.

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Gemstones of Wyoming – Recent Discoveries

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ABSTRACT

Few gemstones other than jade had been described in Wyoming prior to 1975. Field work and research by various prospectors, rock hounds collectors and researchers resulted in discovery of several gemstone, near-gem and lapidary material deposits in Wyoming over the past 3 to 4 decades.

Much of Wyoming is underlain by cratonic basement rocks, and the geology of this craton provides favorable geological environments for discovery of several gemstones – notably diamond, opal, iolite, ruby, sapphire, garnet, jewelry grade gold, platinum and palladium nuggets, and possibly other gems such as emerald, spinel, clinozoisite and zoisite. Gem discoveries in recent years have included diamonds, rubies, sapphires, iolite, peridot, and opal. At least one discovery resulted in the recognition of an enormous, potentially world-class gem deposit, and the possibility of other major deposits is predicted – notably deposits of iolite, opal and diamond have great potential in Wyoming.

Favorable conditions for formation of metamorphogenic gemstones occurred during regional amphibolite-grade metamorphism in Wyoming during the Precambrian. Metapelite in the central Laramie Range hosts index minerals of kyanite, sillimanite and andalusite that provide evidence for high pressures and temperatures that resulted in crystallization of corundum (ruby and sapphire). Cordierite (iolite) formed during a later thermal event. The presence of several undiscovered corundum deposits are predicted based on corundum found in stream sediment samples, and the presence of undiscovered cordierite deposits are predicted based on favorable geological environments. Other gemstones (diamonds, Cape ruby, Cape emerald) are associated with past kimberlitic volcanism in the Late Proterozoic and Early Devonian. Others are the result of more recent processes (opal, agate, jasper).

This paper is dedicated to the memory of Ray E. Harris former Industrial Minerals and Uranium Geologist with the Wyoming State Geological Survey. Ray made many significant contributions to advance our knowledge of industrial minerals in Wyoming and was an active member of the Industrial Minerals Forum.

INTRODUCTION

Prior to 1975, few gemstones other than nephrite jade were known in Wyoming. The lack of gemstone discoveries in the state was due to the lack of research funds and exploration dedicated to this program, which continues to plague progress in a search for gemstones. Even so, several discoveries were made through 2005.

The number of gemstone and lapidary deposits found in Wyoming was significant due to fieldwork, research and prospecting efforts by various agencies and individuals from 1975 to 2005. Some discoveries include diamond deposits (McCallum and Mabarak, 1976; Hausel, 1998a), labradorite (Norma Beers and Letty Heumier, personal communication, 2000), opal (Scott Luers, personal communication, 2002), variscite and minyulite (Bob Bratton, personal communication, 2002), sapphire, ruby, peridot, aquamarine beryl, green beryl, iolite, pyrope garnet (Cape ruby), pyrope-almandine garnet, chromian diopside (Cape emerald), chromian enstatite, jewelry grade gold nuggets, specularite, and several varieties of jasper and agate (Hausel and Sutherland, 2000; Hausel, 2006a). Decorative stone deposits also were found and identified (Harris, 1991, 1994) prior to 2005.

Favorable geological environments exist for several types of gemstones, near-gems, unique minerals and lapidary material, and further research and field studies will lead to additional discoveries. The Wyoming Craton provides favorable geological settings for diamonds and related gemstones. Archean greenstone and high-grade supracrustal belts within the craton are favorable targets for a variety of gems including diamonds, ruby, sapphire, emerald, aquamarine, and jewelry grade gold nuggets; the volcanic terrain associated with the Absaroka Plateau and Yellowstone Caldera is fertile for other gemstones including opal, agate and jasper and the Wyoming basins and Overthrust belt provide favorable terrains for other types of gems.

One research project by the WSGS in the 1980s identified more than 300 kimberlitic indicator mineral anomalies from 1,200 sample sites in the Laramie and Medicine Bow Mountains in southeastern Wyoming. These and other results indicate that Wyoming is underlain by a major diamond province (Hausel and others, 1988; Hausel, 1998a). Some of the sample concentrates also contained grains of gold, aquamarine and corundum from unidentified sources. Only a handful of the mineral trails were ever followed because of budget constraints.

Reconnaissance field surveys resulted in discovery of several corundum deposits and at least one world-class iolite deposit in metapelite, with potential for discovery of one of the largest gemstone deposits on earth. The recognized association of cordierite and corundum with metapelite and certain index minerals almost guarantees other discoveries will be made. Other geological environments in Wyoming may provide hosts for other gemstones such as emerald. Pegmatites in southeastern Wyoming in the vicinity of layered mafic complexes and in the vicinity of metakomatiites in greenstone belts should provide targets for this gemstone. Other possibilities are chrome-rich black shales in the Overthrust belt in western Wyoming. Some excellent gem-quality yellow-green beryl (heliodor) and aquamarine beryl has already been found in some pegmatites at Casper Mountain, Copper Mountain and the Wind River Mountains. Much of the Wyoming basins are blanketed by extensive ash falls from past volcanic eruptions, and these could host some of the larger opal deposits in North America.

GEOLOGICAL SETTING

Cratonic rocks of the Wyoming Craton underlie much of Wyoming. The craton includes Archean (greater than 2.5 Ga) basement rocks of the Wyoming Province that are found underlying Montana and much of Wyoming (Hausel and others, 1991). Along the southeastern margin of the province, basement rocks (Proterozoic schist and gneiss; less than 2.5 Ga) of the Green Mountain terrain abut against the Wyoming Province along the Mullen Creek-Nash Fork shear zone (also referred to as the Cheyenne Belt) (Houston, 1983, 1993). The craton was fragmented during the Laramide orogeny: the style of deformation was brittle and essentially non-thermal. This orogeny resulted in several uplifts that were accompanied by erosion and periodic episodes of renewed uplift.

The basement complex of the Wyoming Province consists of Archean gneiss and schist with scattered greenstone belts and supracrustal terrains that have been intruded by granitic plutons. These supracrustal rocks include thin successions of metapelite mixed with metagraywacke, metavolcanics and gneiss that has been subjected to regional amphibolite-grade metamorphism with isolated upper greenschist metamorphism. The regional prograde metamorphic events appear to have been favorable for genesis of some metamorphogenic gemstones. Metapelites include sillimanite-garnet-biotite-muscovite-quartz schist, kyanite-biotite-corundum-quartz schist, andalusite biotite schist, sillimanite-kyanite-biotite-muscovite-quartz schist, cordierite gneiss and schist, corundum-kyanite schist, etc. Much of the cordierite is considered to be related to Precambrian thermal events that modified some prograde metamorphic rocks.

Corundum- and cordierite-bearing schists and gneisses in pelitic successions are interpreted to represent aluminous shale precursors. One occurrence of corundum-serpentinite in the Granite Mountains may have been the result of regional metamorphism imprinted on aluminous ultramafic magma of possible komatiitic origin. The presence of considerable corundum within a narrow zone of the serpentinite suggests that the schist may have been subjected to site-specific pressure during folding, as there is no obvious evidence for alumina metasomatism. Other aluminous serpentinites have been identified in the South Pass and Seminoe Mountain greenstone belts, although no corundum has been found in those rocks (Hausel, 1991; 1994).

Estimates for burial depth of metapelite in the central Laramie Range are based on the presence of the three alumino-silicate polymorphs (andalusite, kyanite, sillimanite). These all occur in the vicinity of the Elmers Rock greenstone belt. Along the margin of the greenstone belt, Graff and others (1982) identified metapelite with andalusite and sillimanite. A few miles north at Palmer Canyon, kyanite-sillimanite-corundum-mica schist is found near the edge of the greenstone belt. The presence of all three polymorphs within a narrow region of the central Laramie Range supports that the metamorphic grade increased to the north, and the highest-grade metamorphism exceeded the polymorph triple point in the vicinity of Palmer Canyon. The data suggests that these rocks were subjected to lithostatic pressures exceeding 3.8 kb (possibly as much as 5.5 kb) equivalent to a burial depth of 8 to 10.5 miles (12.8-16.8 km) and temperatures exceeding 500°C.

Reports of gem-quality cordierite, corundum and kyanite have been rare until the discovery of the Palmer Canyon deposit, 5 miles (8 km) north of the Elmers Rock greenstone belt in 1995 (Hausel, 2002). The possibility of additional occurrences of gem material in this region is highly probable. This paper focuses on some of the recent iolite discoveries. More detailed information on other gem discoveries are found in Hausel (2006a) and Hausel and Sutherland (in preparation).

WYOMING DISCOVERIES

Corundum may have initially been reported in Wyoming by Aughey (1886) who described corundum near the North Platte River in the Seminoe Mountains of central Wyoming, and reported ruby in limestone. Unfortunately, the descriptions of these appear to be erroneous as there are no known corundum occurrences in the Seminoe Mountains and no known ruby deposits in limestone in Wyoming.

Osterwald and others (1966) described several interesting mineral occurrences and provided a much needed document on the mineral resources of Wyoming. This book became the foundation for later studies of mineral deposits in Wyoming. Jade became a popular item in Wyoming with the discovery of significant detrital deposits near Jeffrey City in the first half of the 20th century (Root, 1977). But primary jade discoveries were restricted to a few, small, low-grade occurrences north of Jeffrey City. To date, the source of the high-quality emerald and apple green jade remains unknown.

Diamonds were accidentally found in kimberlite in 1975 (McCallum and Mabarak, 1976). Later research has shown that the Wyoming Craton has been intruded numerous times by diamondiferous and potentially diamondiferous host rocks including kimberlite, lamproite and lamprophyre (Hausel, 1998a). Associated with diamond are other gemstones including pyrope garnet (Cape ruby), chromian diopside (Cape emerald) and peridot (Hausel, 2005b).

Enormous opal deposits were found in central Wyoming near Riverton. The Cedar Rim opal deposit was mapped over 14 mi^2 and shown to include large resources of common and fire opal, decorative stone and agate (Hausel, 2005a). The presence of secondary precious opal in this deposit suggests that more extensive deposits of this valuable gemstone potentially lie at shallow depth.

Jewelry grade gold nuggets were identified in some of the state's historical gold mining districts, notably South Pass, Douglas Creek, Encampment and Mineral Hill. The possibility for similar nuggets in the Seminoe Mountains is highly likely (Hausel, 2006b,c; 2007).

Corundum (ruby and sapphire) was found in chlorite-biotite schist, vermiculite-biotite schist and mica-kyanite gneiss hosted by Archean orthogneiss within the Wyoming Province. Only one occurrence of corundum has been identified in serpentinite. After the identification of corundum in vermiculite in 1995, a relationship was established between vermiculite schist and corundum, which led to verification that vermiculite is a potential host for corundum (at least five vermiculite schists in Wyoming are now known to contain corundum) (Hausel, 2002).

Cordierite (iolite) has been identified in metapelite in some supracrustal belts, and has also been described in contact metamorphic rocks along the margin of an anorthosite complex in the southern Laramie Range. One of the more interesting reports of cordierite was made by late mineralogist John Sinkankas. According to Sinkankas (1964), massive Wyoming gem-quality cordierite was found in the Laramie Range that was capable of being cut (unfortunately, no location was given). In reference to this same locality, Sinkankas (1959, p. 475) wrote: *"iolite is a widespread constituent of schistose and gneissic rocks in the Laramie Range of Albany County. One estimate has placed the quantity available at thousands of tons. Specimens from this locality examined by the author are glassy broken fragments of rather light blue color, verging towards grayish; small sections are clear and suitable for faceted gems. It is entirely possible that important amounts of gem quality material will be produced from this area in the future"*. When contacted by the author, Sinkankas (personal communication, 2000) could not remember where this deposit was located.

Laramie Range

More than a dozen stream sediment samples collected during a search for diamondiferous kimberlite in the central Laramie Range yielded detrital corundum (less than 2mm) (Hausel and others, 1988). The source of the corundum has yet to be identified, but indicates that the central Laramie Range has good potential for discovery of additional gemstone deposits. This area contains large blocks of metapelite and other alumina-rich rocks that were subjected to amphibolite-grade metamorphism. The presence of these alumina-rich rocks provides fertile ground for alumina-rich gemstones such as ruby and sapphire (Al_2O_3), kyanite and sillimanite (Al_2SiO_5) and iolite [$(Mg,Fe)_2Al_4(Si_5O_{18})$].

Palmer Canyon

A multiple gemstone deposit was identified in Palmer Canyon west of Wheatland during field reconnaissance (Hausel, 2002). This deposit lies along the eastern flank of the central Laramie Range of southeastern Wyoming 16 miles (26 km) west of Wheatland (fig. 1). This community is located along the northern edge of the Denver Basin 70 miles (112 km) north of Cheyenne.

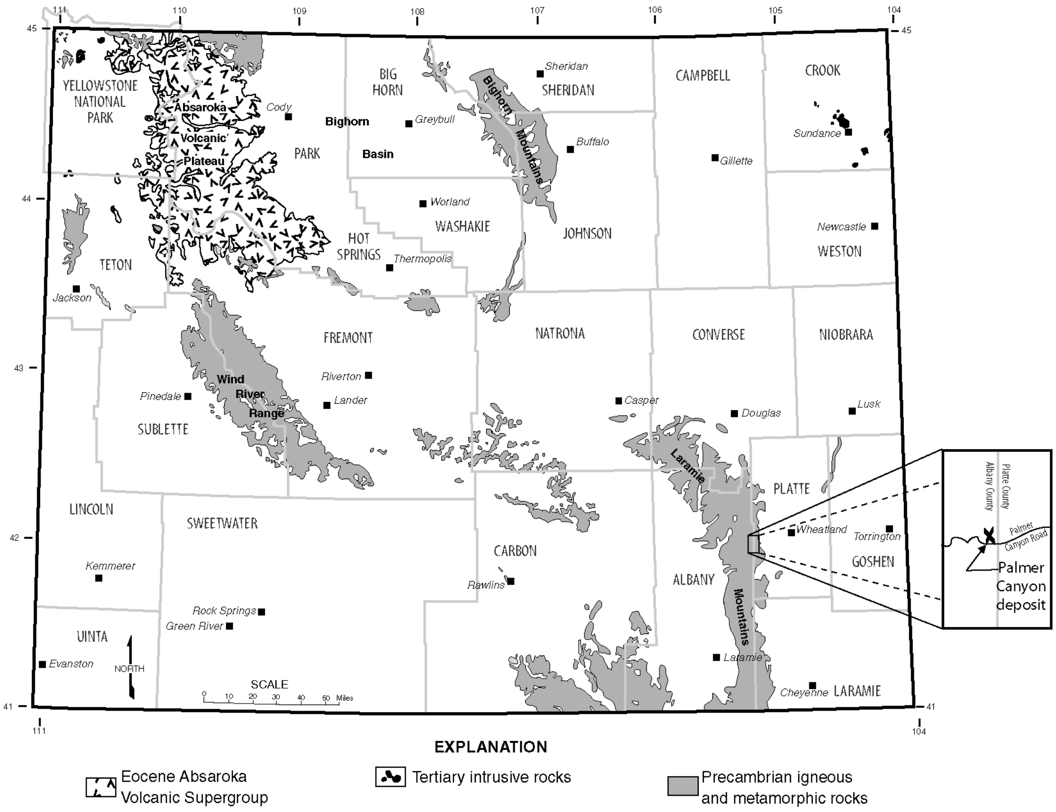

Figure 1. Location map of Palmer Canyon.

The deposit lies within Archean quartzofeldspathic gneiss, granite gneiss, pelitic schist, and biotite-chlorite-vermiculite schist north of the Elmers Rock greenstone belt (fig. 2). There is no evidence that this deposit had ever been investigated for gemstones, even though a shallow prospect pit was dug in the schist prior to 1944 to test the quality of vermiculite. This occurrence originally referred to as the Rolf vermiculite prospect, is N80°W-trending, 65°SW-dipping, biotite schist that locally contains chlorite, kyanite and corundum. Hagner (1944) interpreted the deposit as a replacement of biotite by vermiculite under the influence of pegmatitic fluids. However, pegmatite is not found in the immediate area. Cordierite was not mentioned or identified; furthermore, no descriptions of the corundum were made by Hagner. In the 1930s and 1940s, vermiculite was sought for fire-resistant insulation.

Figure 2. Archean gneiss along the margin of the Palmer Canyon deposit.

During field investigations in 1995, the Roff prospect pit was identified and is about 3 feet (1 m) deep and 5 to 6 feet (1.5-3 m) across. Samples of vermiculite-chlorite-biotite-corundum schist collected from the pit contained as much as 10 to 20 percent corundum (the schist averages about 1 to 5 percent corundum).

Cordierite was discovered nearby by the author. The cordierite is in quartzofeldspathic gneiss a short distance east of the Roff vermiculite pit. The gem was confirmed by XRD analysis (Robert Gregory, personal communication, 1996). The cordierite gneiss crops out over 200 feet (63 m) and has a width of about 10 feet (3.1 m). The gneiss disappears under soil in every direction from the outcrop. Some detrital cordierite found in soil 300 feet (94 m) up-slope from the outcrop, suggests that the deposit has a minimum strike length of 500 feet (156 m).

Samples of cordierite gneiss were collected during initial field investigations. These yielded many transparent cordierite grains including several more than 50 carats in weight. One nodule of facet-grade, massive violet to blue, transparent cordierite was collected that measured 4.25 x 2.5 x 1.25 inches (1,750 carats), which was the largest gem-quality cordierite found in Wyoming, and also believed to be the largest in the world at that time (fig. 3). Gneiss collected from the property contained as much as 20 percent transparent cordierite. Later exploration by Eagle-Hawk mining exposed gneiss in a backhoe trench that contained abundant cordierite.

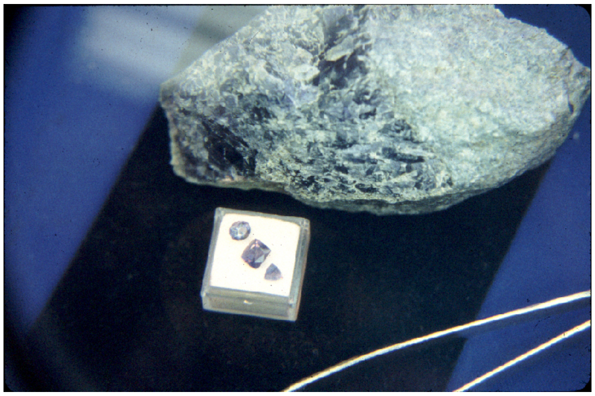

Figure 3. Large (1,750 carat) gem-quality cordierite nodule displayed with three faceted (0.36 to 1.33 carat) iolites from Palmer Canyon.

The cordierite occurs as rounded to disseminated grains and as large nodules. A few nodules are intergrown with quartz. Foliation in the host rock parallels the margin of nodules and in some samples appears to terminate against the nodule boundary providing evidence that the cordierite was formed post regional metamorphism. The host rock is dark gray to light gray cordierite-biotite-sericite-quartz gneiss. Kyanite and sillimanite may also be present, but as minor components. Some secondary calcite is found as crusts on some surfaces and many of the cordierite nodules exhibit a very thin (mm-size) alteration halo of chlorite and sericite.

Three types of cordierite gem materials were recognized: (1) transparent to translucent, violet to blue specimens with poorly developed parting and cleavage; (2) dark-gray transparent to translucent cordierite with distinct parting and cleavage; and (3) dark-gray, cloudy, translucent to opaque cordierite with common mineral inclusions and distinct parting and cleavage. Of these, variety 1 dominates.

Most variety 1 specimens are suitable for faceting. The rough material ranges from pleasing violet to a very light-blue color with only a hint of cleavage and parting. Some variety 1 specimens were later faceted and produced iolite gemstones of excellent color, transparency and pleochroism. Microscopic examination shows a few mineral inclusions in these gems, which are, for the most part, invisible to the naked eye. The inclusions include white acicular grains (possibly sillimanite) and distinct pseudo-hexagonal biotite. Cut gems are free of visible cleavage and parting.

Gray to dark-gray cordierite (variety 2) also exhibits good transparency. This variety has well-developed parting parallel to c{001} and cleavage along b{010}. Many specimens exhibit rectangular cross sections and a few exhibit pseudo-hexagonal habits. A group of cabochons cut from variety 2 cordierite (locally referred to as “Palmer Canyon black”) weighed 0.27 to 3.02 carats (fig. 4). These are dark-gray to black, translucent to opaque, near gems with distinct cleavage, parting and some fractures. Dressing the specimens in silver jewelry enhances their appearance, but otherwise, these are less attractive than variety 1.

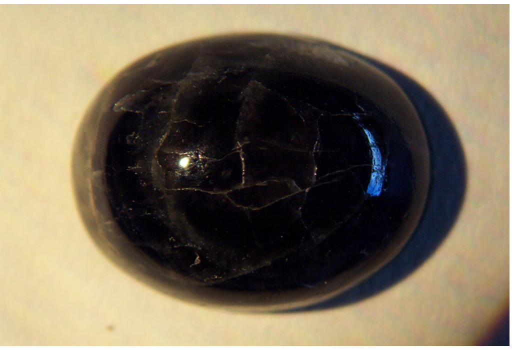

Figure 4. Variety 2 "Palmer Canyon black iolite" 2.51-carat cabochon.

Under first approximation, variety 3 cordierite does not appear to be suitable for gem material as the faceted material has many flaws. Two samples of variety 3 were faceted by Eagle-Hawk mining and yielded a 3.9-carat lozenge-cut stone, and a 3.4-carat marquise. Both stones were extensively flawed with visible cleavage, parting, and some visible mineral inclusions. However, after these were mounted in gold necklaces, they produced surprisingly attractive jewelry (fig. 5). Other specimens of variety 3 cordierite are gray to cloudy. Microscopic examination of these samples revealed mylonitic to ultra-mylonitic texture.

Figure 5. Palmer Canyon gemstones dressed in gold. (a) 3.9-carat cordierite, (b) less than 1 carat iolite, and (c) 1.1 carat reddish-pink sapphire (photos courtesy of Chuck Mabarak).

Unlike cordierite, only a small amount of corundum at Palmer Canyon is gem quality. The corundum schist at Palmer Canyon was traced for nearly 1,000 feet along strike. Samples of the corundum-chlorite-biotite schist contain minor kyanite and uncommon sillimanite. Spectacular foliated kyanite-mica-schist adjacent to the corundum schist, exhibits abundant 1 to 2 inch-long (2.5-5 cm) blades of kyanite with minor to trace corundum. The corundum occurs as hexagonal prism and plate porphyroblasts. The largest prism found by the author is a 1-inch (2.5 cm) prism with 0.3-inch (0.75 cm) diameter. The largest plate measured 0.4 inch in diameter. Larger specimens, some of which have good translucency and a pleasing pink to red-pink color, were later found by Eagle-Hawk mining (Vic Norris, personal communication, 2002). The corundum typically averages 0.2 inch (0.5 cm) in diameter.

Three categories of gem and near-gem corundum occur on the property. These are: (1) reddish-pink transparent to translucent corundum (sapphire) (fig. 5), (2) light-pink translucent corundum (pink sapphire), and (3) white to light pink translucent to opaque corundum. Microscopic examination of a limited number of corundum specimens shows mineral inclusions to be relatively common.

Some corundum fashioned from this property included a brownish-pink opaque, 1.4-carat cabochon, and a near-perfect red transparent, 1.1-carat marquise with few flaws (fig. 6). Other faceted sapphires included gemstones of 0.75 to 3 carats in weight (Vic Norris, personal communication, 2002). Some cabochons yield pleasing, light-pink sapphires, but most faceted light-pink corundum is less attractive due to common, visible mineral inclusions.

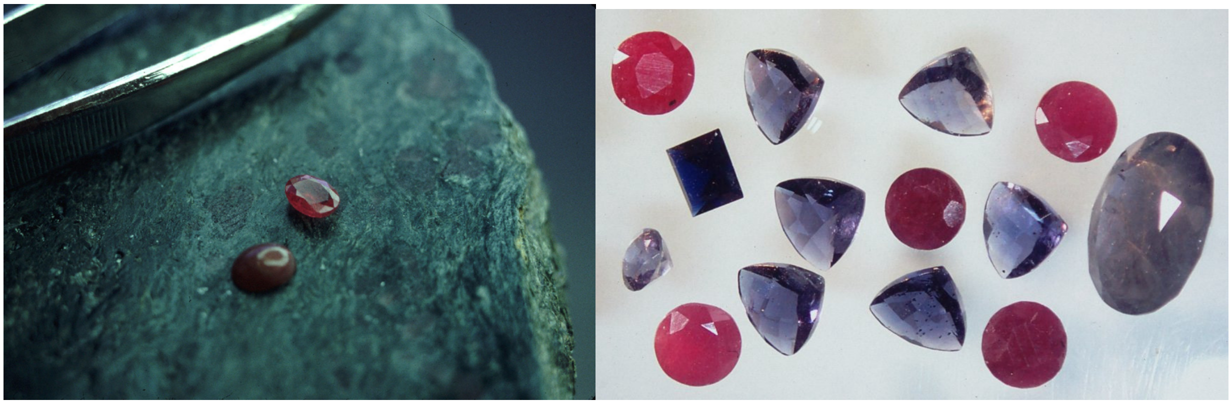

Figure 6. (a) Brownish-pink (1.4 carat) cabochon and a reddish pink (1.1 carat) faceted sapphire sit on corundum schist. (b) A parcel of iolite and sapphire gemstones from Palmer Canyon (courtesy of Vic Norris).

Grizzly Creek

Following discovery of the Palmer Canyon iolite (Hausel, 1998b), it became clear that similar deposits were likely to be found. The later thermal metamorphic event responsible for the large cordierite porphyroblasts at Palmer Canyon appears to have been relatively widespread in the central portion of the Laramie Range. While the earlier prograde metamorphic event produced large porphyroblasts of kyanite in the adjacent rocks. The kyanite represents a good indicator mineral in the search for alumino-silicate and alumina gemstones in this region. Thus, the search for similar metapelites resulted in another significant gemstone discovery south of Palmer Canyon – one that is likely a world-class discovery, but will need further exploration and research to fully appraise.

Based on geology, Grizzly Creek became a primary target for similar gemstones to those at Palmer Canyon (fig. 7) (Hausel and Sutherland, 2000). Field reconnaissance was conducted in this area after obtaining permission to access the area through a private ranch. During the initial field investigation, it became clear that a major gem deposit had been discovered. Very large masses of gem-quality iolite were found with large quantities of gem-grade kyanite.

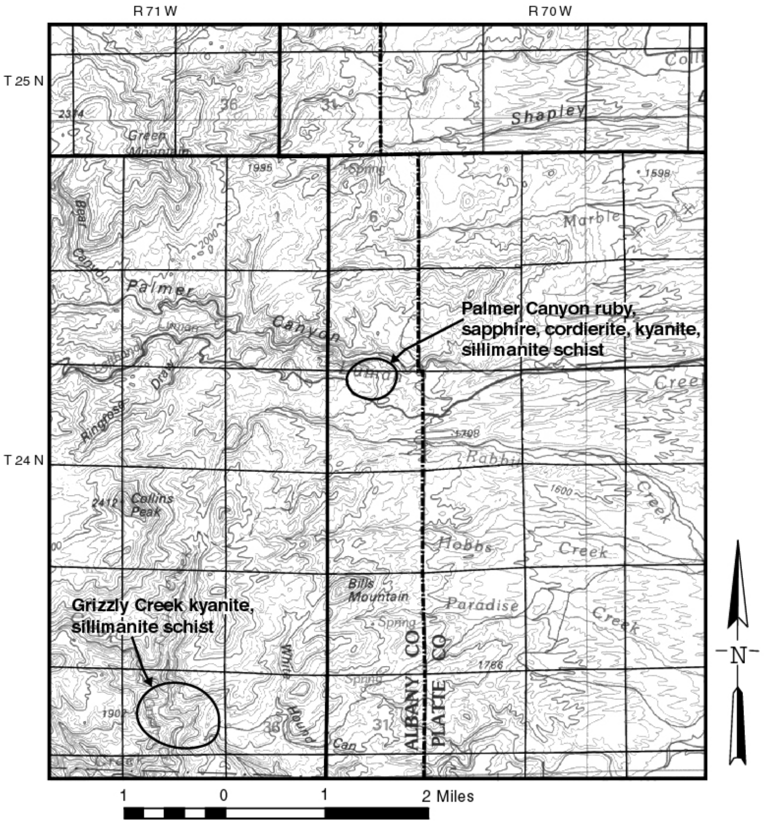

Figure 7. Location of Grizzly Creek.

The cordierite at Grizzly Creek is surrounded by kyanite and sillimanite schists that contain minor corundum. The kyanite and sillimanite schist lies in a 300 by 5000 foot (94-1,560 m) belt of metapelite. During geological mapping by George Snyder of the U.S. Geological Survey, a collector's quarry was identified that yielded a couple of nice specimens of ruby (George Snyder, personal communication), but the cordierite and kyanite was essentially overlooked as gem material.

Much kyanite appears to be cabochon grade and has a very pleasing, sky-blue color with some tawny and pink specimens (fig. 8). Iolite found nearby is massive and forms large replacements of the schist. This one deposit may represent the largest iolite occurrence in the world. During reconnaissance, specimens of massive iolite were collected including one football-size transparent gemstone that weighed 24,150 carats – the largest iolite gem found on earth (fig. 9). However, this stone is dwarfed by masses of material that remain in place in Grizzly Creek. Some of the massive gem material will require quarrying operations to recover. Even so, based on the large masses that were recognized, it is very likely that gem specimens more than 1 ton (more than 4.5 million carats) in weight could be recovered! However, the quality of the material needs to be thoroughly appraised and the deposit mapped in detail. In outcrop, the iolite is weakly iron stained and shows excellent light blue color and transparency on fresh surfaces. But, it is not known how much if any of this material has been destroyed by mylonitization. For example, several specimens collected at Palmer Canyon showed distinct mylonitic to ultramylonitic texture in thin section that resulted in a cloudy, light-blue and glassy material of poor quality.

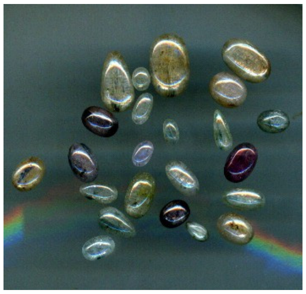

Figure 8. Kyanite cabochons cut from material collected in the central Laramie Range (photo courtesy of Vic Norris).

Figure 9. (a) Large football-size iolite gemstone from Grizzly Creek is dwarfed by massive specimens in outcrop. (b) Wayne Sutherland of the WSGS sits in front of weakly iron stained iolite outcrop. The massive iolite forms much of the outcrop behind Sutherland and extends from his hat to the pack at his feet and continues upward from his right elbow to the top of the photo. This specimen potentially weighs several tons!

Such discoveries need to be followed up with detailed field and laboratory work, which could result in a new, major natural resource industry. Iolite currently sell for $30 to $150 per carat and only costs about $1 to facet. Additionally, iolite gemstones greater than 5 carats are essentially unheard of. This deposit potentially hosts tens of millions to hundreds of millions of dollars worth of iolite.

Raggedtop Mountain Deposit

An extensive deposit of cordierite is described in the Laramie anorthosite-syenite complex in the central Laramie Range (southeastern Wyoming) several miles south of Palmer Canyon and 15 miles (24 km) northeast of Laramie. Newhouse and Hagner (1949) and Osterwald and others (1966) reported widespread lenticular to tabular layers of cordierite in metanorite (hypersthene gneiss), gneiss and syenite along the southern margin of the anorthosite complex (1.5 Ga) in sections 13, 14 and 24, T. 17 N., R. 72 W. and sections 17, 18, 19 and 20, T. 17 N., R. 71 W.

The host rock is described to locally contain 50 to 80 percent cordierite (this deposit has not been investigated for gemstones, although based on its size it is possible that this is the deposit referred to by Sinkankas, (1959, 1964)). The occurrence lies about 0.5-mile west of Raggedtop Mountain, less than 1.8 miles (2.9 km) north of Dirty Mountain, in a belt 0.3 to 1.2

miles (0.5-1.9 km) wide and about 6 miles (9.6 km) long. The host gneiss is highly foliated, intensely folded and contorted.

Subbarayudu (1975) reported the host as cordierite-hypersthene gneiss, interpreting it to be a paragneiss formed during contact metamorphism of sedimentary rock. Where found, the cordierite is fresh and clear and slightly altered to pinite along fracture planes and may enclose inclusions of zircon and spinel. The formation temperature of the cordierite was estimated at 1,000°C (Miyashiro, 1957).

Howard (1952) described the weathered cordierite to have dark brown surfaces, but yielded blue or bluish gray massive material on fresh surfaces. In thin section, the cordierite was described to form colorless, subhedral to anhedral grains ranging from a fraction of a millimeter to 1 mm across with a refractive index of 1.542 to 1.550. Well-developed polysynthetic twinning is common, but some cordierite is untwined.

Unfortunately, much of the deposit is currently inaccessible on private property. The author was able to obtain small samples from the disseminated margin of this deposit. Although the material sampled by the author was small and granular, all was gem-quality and in grains typically 1 carat or less in weight. The massive portions of this deposit described by Newhouse and Hagner (1949) remain unevaluated for gem material. This could represent another world-class gem deposit. Based on the reported resource estimate of more than 450,000 tons of cordierite, there is a potential for more than 2,041,000,000,000 carats of cordierite! If only 10 percent of this material is facetable, this could represent one of the largest gemstone deposits on earth with potential value that could dwarf Wyoming's oil, gas, uranium, and coal industries. Again, there is no current research scheduled for this deposit.

Other iolite, kyanite, sapphire, and ruby deposits may occur. Hausel and Sutherland (2000), describe other occurrences worthy of exploration.

Wind River Mountains – Copper Mountain

Cordierite was described in the South Pass greenstone belt in the Wind River Mountains of western Wyoming (Hausel 1991), and identified in the Copper Mountain supracrustal belt of the Owl Creek Mountains in northwestern Wyoming (Hausel and others, 1985). Cordierite in these two metamorphic belts is described as opaque, black to brown, rounded porphyroblasts typically less than 0.5 inch (1.3 cm) across. Many mineral grains are partially to entirely replaced by fine-grained sericite and quartz; no gem material is known from either area, but there has been essentially no research related to gemstones in these two districts.

Abundant industrial placer corundum with some *"dark, rich red"* rubies (including star rubies) is found in the Big Sandy opening in the southern Wind River Mountains, western Wyoming (Spendlove, 1989). The source of this corundum has not been identified. Detrital corundum has been dredged by hobbyists at Grass Creek (a tributary of the Big Sandy) in section 15, T. 30 N., R. 104 W. (Joe Sims, personal communication, 2003), and specimens up to 80 carats have been recovered. The 80-carat corundum shows rounding of the hexagonal prism, which may be due to stream abrasion. Much of the corundum is reddish to reddish-brown, opaque to translucent. The source for the material is thought to lie to the north in the Wind River Range, were specimens of corundum schist with transparent to translucent, pinkish-red sapphires have been found in mica schist (Ron B. Frost, personal communication, 2003).

Sierra Madre Mountains

Cordierite is also described as almond-shaped grains in schist in the Sierra Madre southwest of Encampment in southeastern Wyoming. Again, this material has not been investigated for gemstones. A ruby and a grass-green, transparent beryl were found in pegmatite in the Sierra Madre (Larry Clark, personal communication). The location of the discovery was not revealed.

Powder River Basin

Cordierite is reported in baked shale and clays above some coal burns in the Powder River Basin in northeastern Wyoming (Osterwald and others, 1966). Descriptions of the material were not given.

Platte Valley

Corundum was found in vermiculite in the Platt River valley along the edge of the Medicine Bow and Sierra Madre Mountains in southeastern Wyoming. One deposit at Baggot's Rock is described as specks of corundum with kyanite and vermiculite in biotite- and hornblende-schist (Osterwald and others, 1966). The deposit was mined on a small scale for vermiculite from 1937 to 1941 (Hagner, 1944).

A few miles south, an open cut dug for vermiculite in granite-gneiss in the Homestead Draw area contains scattered pockets of ruby. Some have reaction rims of green zoisite similar to those at the Red Dwarf ruby deposit in the Granite Mountains. Rubies were also found in a second vermiculite deposit on the Platte Ranch to the southwest (Ralph Platt, personal communication, 1998).

Granite Mountains

Corundum was reported at a few localities in the Granite Mountains, central Wyoming. Some gem-quality corundum was described in alluvium along the Sweetwater River both east and west of Jeffrey City. Pinkish-red sapphires up to 0.25-inch (1 cm) in diameter were found in pelitic schist in NE SE NE section 31, T. 31 N., R. 89 W. of the McIntosh Meadows Quadrangle in the northeastern Granite Mountains (Sutherland and Hausel, 2002). The corundum is very limited in extent. Deep- to purplish-red ruby was described near Sweetwater Divide. Some specimens were cut and produced star-rubies (Curtis, 1943).

Corundum was also found on the Robinson Claim in the Rattlesnake Hills of the northeastern Granite Mountains. One specimen of purple-red, opaque to translucent hexagonal corundum from the deposit was a little more than 1.25 inches (3.2 cm) in diameter.

Abernathy sapphires

Sapphires were recovered from the Abernathy deposit 40 miles east of Lander. The pale-blue to white sapphires were described in N25°E-trending mica schist enclosed by gray-brown granite near Sweetwater Station. Abundant 1-inch (2.5 cm) diameter nodular ‘sapphires’ were found that were badly shattered and altered on the edges (Love, 1970). According to Hagner (1942) these are poor quality gray to dirty-blue, cloudy corundum that were exposed in a 5 x 5 x 8 foot prospect pit. The biotite-corundum schist is about 4 feet wide. Pale to bright-red rubies were found in mica schist north of the Abernathy deposit at the Marion prospect. Some of these were cut into gems (Osterwald and others, 1966).

Other rubies were found as float in the Granite Mountains. According to Love (1970), soft green mica schist boulders with dark-red rubies were found near Muskrat Creek in the Wind River Formation (Eocene) near Beaver Rim, west of the Gas Hills uranium district, 12 miles (19 km) north of the Red Dwarf ruby deposit. These rubies were up to 1 inch (2.5 cm) in diameter and highly fractured. The source of the schist was not determined.

A nearby placer with abundant, bright-red (greater than 1 inch in diameter), fractured rubies was reported (Osterwald and others, 1966). Chloritic schist float with rubies (similar to the Red Dwarf schist) was also found in the Crooks Gap Conglomerate (Tertiary), along the northern flank of Green Mountain, about 15 miles (24 km) to the southeast of the Red Dwarf (Avon Brock, personal communication, 1982; Hausel, 1986).

Red Dwarf

The Red Dwarf lies a few miles northwest of Jeffrey City (sections 13 and 24, T. 30 N., R. 93 W.). The host rock is corundum-bearing quartzofeldspathic gneiss with a strike length of 5,000 feet (1560 m) and widths that vary from 20 to 50 feet (6.25-15.6 m) (Hausel, 1997). The gneiss grades from gray quartzofeldspathic gneiss along its northern end to chloritic schist along its southern end. It typically contains 1 to 10 percent corundum as porphyroblasts enclosed in fuchsite-zoisite reaction rims (fuchsite was confirmed by XRD – Robert Gregory, personal communication, 1998).

The largest specimens of Wyoming corundum were found here. These include a specimen collected by the author that was about the size of a hen's egg, which measured more than 2.5 inches (6.4 cm) across. A specimen collected by J. David Love of the U.S. Geological Survey was a large fuchsite-zoisite pseudomorph after corundum with small (0.25 to 0.5 inch) specs of preserved purplish-red ruby. Only half of the original sample remains but measures more than 5 inches (12.7 cm) in length and 3 inches (7.6 cm) across.

A few Red Dwarf specimens were cut into cabochons, but none have been faceted primarily due to the translucent to cloudy nature of the corundum. The fashioned stones are purplish-red (none have been tested for heat treatment). One specimen yielded a 2.77 carat ruby cabochon that shows a couple of parting planes on the stone, but otherwise is an attractive gem. A few specimens of gem-quality ruby cabochons with excellent asterism were produced from this deposit in past years (George Devault, personal communication).

In addition to the Red Dwarf gneiss, a serpentinite located a short distance west, contains small (average 2 mm diameter), light-blue, translucent to opaque corundum (Robert Odell, personal communication, 1998). Locally, this rock contains as much as 20 percent corundum (Hausel and Sutherland, 2000).

Overall, the Red Dwarf material produces pleasing, purplish-red rubies and corundum that is translucent to opaque. The lack of transparency of this material greatly diminishes its value and research in clarification processes (heat treatment) is needed.

CONCLUSIONS

Based on research over the past few decades, several gemstone and near gemstone localities have been identified (Hausel and Sutherland, 2000). Most of the discoveries remain relatively unexplored.

The possibility of finding additional gemstone deposits in Wyoming is considered very high, as most of Wyoming's mountain ranges are cored by amphibolite-grade schists and gneisses, which include successions of metapelites that are considered favorable hosts for metamorphogenic deposits.

Recent field investigations have shown a correlation between metapelite, corundum and cordierite, as well as a strong correlation between corundum and vermiculite: about 10-20 percent of the vermiculite deposits investigated to date, contain corundum. Thus further investigations of vermiculites as well as other metapelites, will undoubtedly lead to other corundum and cordierite occurrences.

Other types of gemstones are also likely to be found in significant deposits. Most notable are diamonds and opals, but more research and exploration are needed.

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A New Kaolin Province in Guyana and Suriname

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ABSTRACT

Guyana and Suriname are located on the northeast coast of South America. Both countries are noted for their high quality bauxite deposits. Underlying the bauxite deposits are sedimentary kaolins which were the precursors of the bauxite that were developed by intense tropical weathering. These kaolins average about 6 meters in thickness. The kaolin was derived from Precambrian granitic areas to the south, which extend into northern Brazil. The sedimentary kaolins are lower Eocene in age. Many of the kaolin deposits under the bauxite are good quality with high brightness and good viscosity which are necessary for their use as coating kaolins. There are several millions of tons of kaolin reserves. These kaolins have been evaluated over the past twenty years but because of political, infrastructure, and logistical problems, they have not been developed. The physical and chemical characteristics of these kaolins are presented.

INTRODUCTION

Bauxite mining in Guyana and Suriname is the major activity in both countries and is the largest export commodity. Guyana provides the major refractory grade of bauxite that is used in North America. The bauxite occurs in the Onverdacht Formation of lower Eocene age. The major alumina mineral in these high quality bauxites is gibbsite. Underlying the bauxite in both countries is kaolin which is the parent material from which the bauxite formed as a result of intense tropical weathering (Vletter, 1963).

The kaolin was derived from Precambrian granites that occur in the shield area in Southern Guyana and Suriname which extends into Northern Brazil. The kaolinitic weathering material was transported and deposited in a belt which parallels the current coastline of both countries. These kaolins have been drilled and tested since 1973.

Guyana Kaolin

In 1973, the Guyana Government, in conjunction with Nissho-Iwai Co., Ltd. of Japan, did a study of the kaolin at the Topira Mine in Ituni (fig. 1). The goal was to establish a processing plant to produce kaolin products for use in the ceramics and paper industries. This project was never completed. In 1976, the Minister of Energy and Natural Resources established a Kaolin Beneficiation Planning Committee which was to find a joint venture partner to build a 250,000 metric ton processing plant.

Figure 1. Location map of the Topira deposit in Guyana

Figure 1. Location map of the Topira deposit in Guyana.

In 1977, the United Nations Industrial Development Organization prepared a report on the production of refined kaolin for the Kaolin Beneficiation Planning Committee. Test work by Guyanese, Japanese, and German Democratic Republic sources indicated that paper coating clay, filler clay, and refractory and ceramic kaolins could be produced from the kaolin deposit at Topira. The mineable resources in the Topira deposit were determined to be over 4 million metric tons. The thickness of this kaolin averaged 30 feet. The overburden is minimal because the bauxite has been mined and only the iron stained upper 3 or 4 feet would need to be removed. Other kaolin deposits in the immediate area are Warababaru and Kamakabra. The Topira deposit is approximately 120 miles south of Georgetown.

In 1979, International Trading Company (ITC), headquartered in Baltimore, Maryland, contracted with BIDCO (Bauxite Industries Development Co., Ltd.) to do a comprehensive feasibility study on Guyana kaolin. ITC represented Georgia Kaolin Company in Asia and South America. ITC contracted with H.H. Murray and Associates to do the evaluation of the Topira kaolin deposit. Four locations on the deposit were staked and core drilled. The cores ranged from 20 to 38 feet in length and were sampled in 5 foot increments. The physical property composite results are shown in Table 1.

Table 1. Physical properties of the Topira kaolin deposit.

Drill Hole #	% Grit	% Minus 2 Microns	Leached Brightness	Brookfield Viscosity	Hercules Viscosity
1	8.2	92	88.3	464 cps @ 68% solids	18 dynes @ 67% solids
2	7.6	87	85.7	420 cps @ 69% solids	18 dynes @ 67% solids
3	6.2	88	86	426 cps @ 66% solids	18 dynes @ 66% solids
4	9.2	89	91	472 cps @ 68% solids	18 dynes @ 68% solids

Core sample #3 was run through a 2 Tesla wet magnetic separator with 2 minutes retention time. The brightness improved from 86 to 90.4. X-ray diffraction of the core samples showed that the reason for the relatively high Brookfield viscosity was the presence of 3 to 5 percent montmorillonite. The specification for Brookfield viscosity of coating grade kaolins is 300 cps maximum at 70 percent solids.

The Hercules hi-shear viscosity specification for coating grade kaolins was 18 dyne maximum at 70 percent solids.

A 5 ton bulk sample from the Topira deposit was shipped to Georgia Kaolin Company in Dry Branch, Georgia for evaluation in their pilot plant. The results of this pilot plant evaluation are shown in Table 2.

Table 2. Physical properties of the 5 ton bulk sample.

Crude Brightness	% Grit	Particle Size	Leached Brightness	Magnet Brightness	Brookfield Viscosity	Hercules Viscosity
81.2	5	90% >2 microns	85	87	560 cps @ 68% solids	18 dynes @ 68% solids

Core sample #4 was fractionated to 90 percent less than 2 microns and calcined at 1050°C. The calcined sample brightness was 91.8.

ITC evaluated the results and found the kaolin brightness was very good but the low and high shear viscosity was high and considerably above the specification required for Japanese coating clays which was ITC's main market. Therefore, ITC did not pursue the project further.

Suriname Kaolins

Suriname, formerly known as Dutch Guiana, is located in northeastern South America between Guyana and French Guiana (fig. 2). The climate of the region is tropical with an average annual temperature of 26°C. The average rainfall in Paramaribo, the capital, is 2280 mm per year. There are two rainy seasons, one from May through September, and another from December through February (Broekstra, 1986). This tropical climate caused intensive weathering of the granitic highlands to the south during Tertiary and Quaternary time when the residual weathered material was transported and deposited on the coastal plain. After the deposition of the kaolin and kaolinitic sands, they were bauxitized, thus forming the Onverdacht, which is divided into the Upper Onverdacht and the Lower Onverdacht (Aleva, 1965). The Upper Onverdacht consists almost exclusively of bauxite and the Lower Onverdacht of kaolin and kaolinitic sands. Below the kaolin and kaolinitic sands are weathered Precambrian granites and gneisses (Moses and Mitchell, 1963).

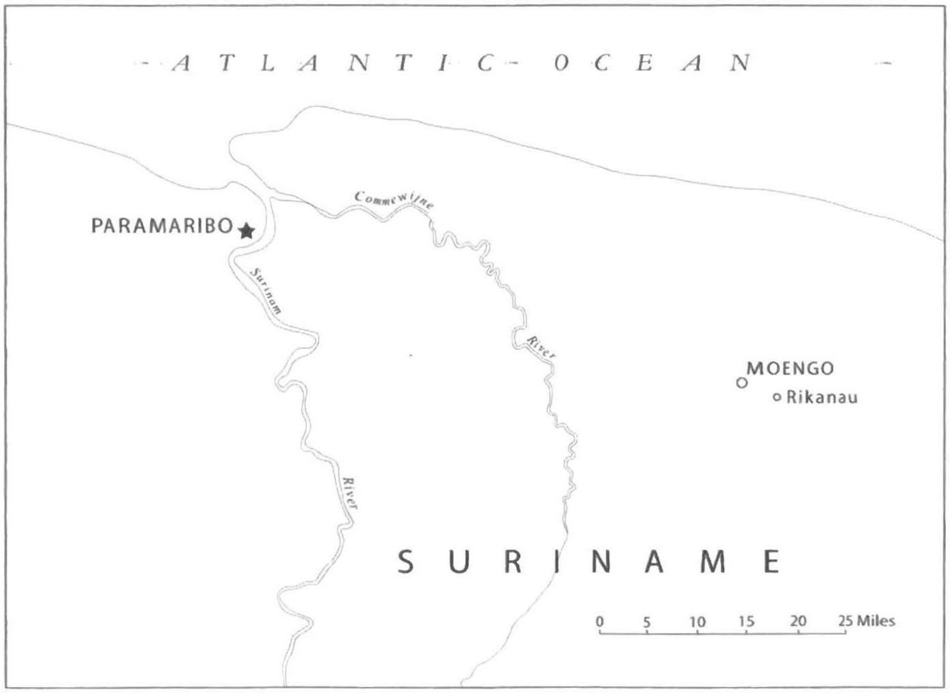

Figure 2. Location map of the
Rikanau deposit in Suriname

Figure 2. Location map of the Rikanau deposit in Suriname.

In 1983, the Aluminum Company of America (ALCOA), after mining the bauxite at the Rikanau deposit near Moengo (fig. 2), decided to investigate the kaolin deposit. Their plan was to build a kaolin processing plant at Moengo to produce a full range of coatings and filler grades for export if the drilling and testing showed that the quality was good. Drill cores were spaced at 200-foot intervals on the Rikanau deposit and the reserve was determined to be 20,000,000 tons.

ALCOA built a kaolin testing laboratory in Milledgeville, Georgia. Core samples were sent there and to Indiana University for evaluation. The average thickness of the kaolin was 20 feet. The upper 5 feet were iron stained and contained considerable gibbsite and large muscovite flakes. The core samples were tested for percent grit; crude, degritted, and processed brightness, particle size distribution, and viscosity as shown in Table 3.

Table 3. Average physical properties of the Rikanau kaolin.

Crude Brightness	Degritted Brightness	% Grit	Particle Size	Leached Brightness	Magnetic Brightness	Brookfield Viscosity	Hercules Viscosity
81	83	6	65 to 80%	80% < 2μ 86 ← 89 90% < 2μ 88 ← 90		80% < 2μ 400 cps → 4 dynes 90% < 2μ 360 cps → 3 dynes	

Two large test pits were dug and 5 tons from each were shipped to the Milledgeville lab. These test pit samples were evaluated at the Georgia Kaolin Co. pilot plant at Dry Branch, Georgia. The results confirmed the data shown in Table 3, and the quality results indicated that #1 and #2 coating grade kaolins could be produced; #2 quality was 80 percent less than two microns in particle size, and #1 quality was 90 percent less than two microns. Typical electron micrograph of the Rikanau kaolinite (fig. 3) and gibbsite crystals (fig. 4) in the upper 5 feet of the deposit are shown.

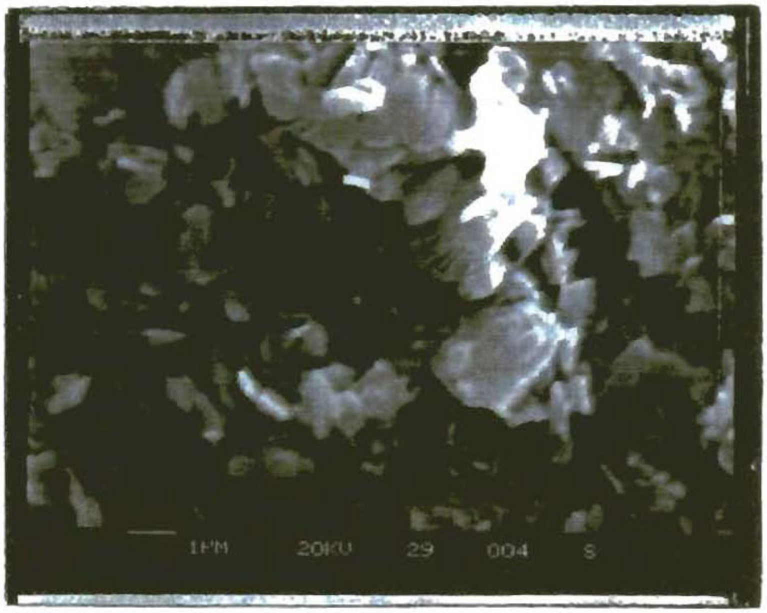

Figure 3. SEM of the Rikanau kaolinite

Figure 3. SEM of Rikanau kaolinite.

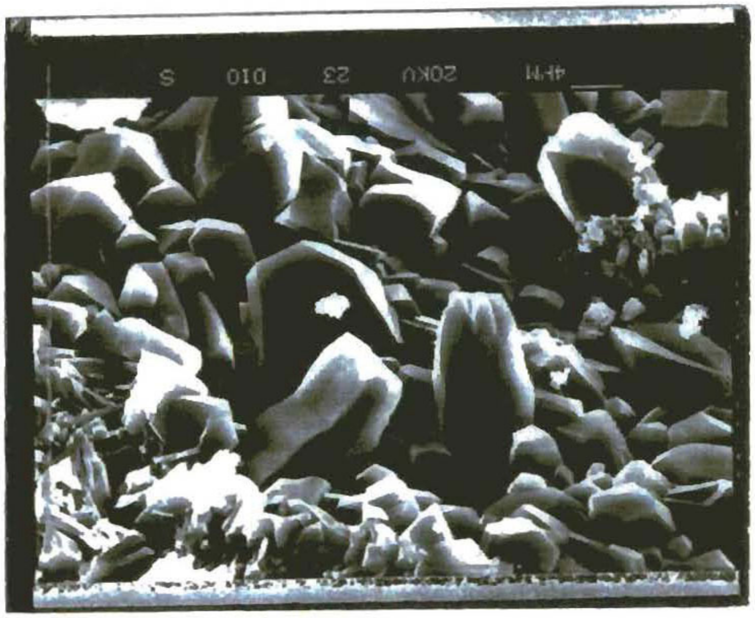

Figure 4. SEM of Gibbsite

Figure 4. SEM of Gibbsite.

Even though the test results were good, ALCOA determined that the logistics of shipping the finished kaolin by barge to the port at Paramaribo and transloading from the river barge of 500 tons to a 5000 ton ore carrier, which was the maximum limit that could navigate the sand barriers at the mouth of the river, were too costly so decided not to go forward with the project. However, now the sand bar has been dredged so that 15,000 ton vessels can leave Paramaribo.

In 2004, Global Optimum B.V., a Suriname company, decided to restudy the Rikanau deposit. The company drilled several core holes between the 200-foot holes that ALCOA drilled. The goal of Global Optimum was to make a 90 brightness coating clay. The core samples were sent to a kaolin pilot plant located in Eatonton, Georgia and to Indiana University for testing. Two test pits were dug and the kaolin from them was shipped to Eatonton. In general, the test results were similar to those obtained by ALCOA. However, an additional process, selective flocculation, was also used. The results of the selective flocculation process showed that a coating grade kaolin with a brightness of 90.5 to 91 could be made. There are three additional areas where the bauxite has been removed that contain kaolin similar to the Rikanau deposit. This project is still ongoing.

SUMMARY

Kaolins which underly bauxite in Guyana and Suriname have been evaluated to determine if the quality is good enough to produce paper coating clays. The results have been positive but because of political, infrastructure, and logistical problems, these deposits have not yet been developed. However, the Rikanau kaolin deposit in Suriname is currently being evaluated again.

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Chemistry and Mineralogy of the Turquoise Group of Semi-Precious Gem Stones and Their Facsimiles

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ABSTRACT

Turquoise is one of those semi-precious gem stones that have never really been explored for but instead almost always found as a secondary mineral of copper deposits. However in some instances, it occurs by itself for unexplained reason in a non-copper deposit environment, such as at Cerrillos and OroGrande, New Mexico, northern Nevada and Cripple Creek, Colorado.

When you look at the mineralogy and chemistry, turquoise becomes a gem stone possessing many properties based mostly on its chemistry which in turn is responsible for all the varying hues of color that commonly occur in turquoise. The question becomes whether a true turquoise actually exists having a composition of $Cu\ Al_6\ (PO_4)_4\ (OH)_8.4H_2O$.

Turquoise forms a chemical series with the mutual substitution of Fe^{3+} for Al^{3+} forming Chalcosiderite at the far end of the series with a composition of $Cu\ Fe_6\ (PO_4)_4\ (OH)_{8.}\ 4H_2O$. There are four minerals in the middle of this group that are all hydrated phosphates and vary only by the amounts of Cu, Fe^{2+}, Zn and Ca which can all substitute for Cu and still produce the colors associated with "turquoise".

Most "turquoise" is deficient in Cu and only in rare instances do materials called or labeled turquoise contain Cu as the principle constituent in the divalent site. The x-ray diffraction data for all of the minerals in the turquoise group have almost identical d spacing which makes identification difficult without corresponding chemical analyses. Since most samples of "turquoise" are cation deficient, the probability of a true turquoise mineral occurring in the western U.S is doubtful.

With the popularity of turquoise as a jewelry stone and the lack of any real, untreated natural turquoise, many associated mineral and facsimile materials have entered the market place. Because of this, turquoise has had its mineralogy and popularity undermined by the introduction of treatments, imitations and synthetics. Some of these facsimiles are difficult to detect even by the experts. Other minerals which are sometimes called turquoise such as chrysocolla, variscite and gaspeite are attractive semi-precious gem stones in their own right. Gaspeite in particular is often more costly than turquoise.

Over 60 percent of all Turquoise currently being mined in the U.S. is stabilized to some degree. The price increases significantly for untreated natural turquoise

INTRODUCTION

One of the least understood semi-precious gem stones is turquoise and, in particular, that turquoise coming from deposits in the western U.S. The one true mineral turquoise is from Lynch Station, Campbell County, Virginia as reported on by Schaller (1912). This turquoise has been the standard for the mineralogy textbooks by Dana (1932, 1951, 1977). The most comprehensive study of turquoise can be found in Pough (1915).

The western U.S. produces more "turquoise" than anywhere else with the possible exception of China, yet there has been very little work done on the material coming from these deposits. Turquoise being sold in the western jewelry outlets in the southwest contain "turquoise" of every imaginable turquoise color hue set in silver and gold and all sold as genuine turquoise. Upon questioning, most of the dealers selling this jewelry did not know the locality or history of the stone except what they were told by the sellers of the stones. So, what is the turquoise being mined in the western U.S. and sold in the tourist areas of the southwest?

Turquoise Group of Minerals

Theoretically, the mineral turquoise in its purist form is a copper aluminum phosphate hydrate, $CuAl_6 (PO_4)_4(OH)_8.4H_2O$. As shown in Table 1, this turquoise is the Al end member of a group of five other minerals forming a complete chemical series with the Fe^{3+} end member chalcosiderite, $CuFe_6(PO_4)_4(OH)_8.4H_2O$. The intermediate members can contain varying amounts of Cu, Fe^{2+}, Fe^{3+}, Zn and Ca, all which can substitute for one another and still produce the colors associated with "turquoise". A general formula for the turquoise group is $A_{O-1}B_6 (PO_4)_{4-X} (PO_3OH)_X.4H_2O$, where A=Cu, $Fe^{2+,}$ Zn, Ca and B=Al, Fe^{3+} and x= 0 to 2 (Foord and Taggart, 1998).

Most "turquoise" is deficient in Cu and rarely does material called turquoise contain Cu as the principal member of the A site. In the Cu, Fe^{3+} end member chalcosiderite, the amount of Cu in the A site will vary with a vacancy.

Table 1. Turquoise mineral group.

Turquoise	$Cu\ Al_6\ (PO_4)_4\ (OH)_8.4H_2O$
Planerite	$\_\_\_Al_6\ (PO_4)_2\ (PO_3OH)_2\ (OH)_8.4H_2O$
Faustite	$(Cu,Zn)\ Al_6\ (PO_4)_4\ (OH)_8.4H_2O$
Aheylite	$(Zn,Fe)\ Al_6\ (PO_4)_4\ (OH)_8.4H_2O$
Chalcosiderite	$Cu\ Fe_6\ (PO_4)_4\ (OH)_8.4H_2O$

Turquoise

Turquoise can vary in color from deep blue, blue, light blue, blue-green green to greenish-gray. All of these colors depend on the relative amounts of the cations in the A site. Based on chemical tests of turquoise from 21 mines in several different countries, it was found that the CuO content varied from less then 2 percent up to 9 percent, Al_2O_3 from 29 percent to 54 percent and P_2O_5 from 14 percent to 39 percent. The water content is critical and will range only from 17 percent to 18 percent H_2O (Anderson, 2006).

This paper is only on western U.S. "turquoise" and the chemistry of these deposits will be fully discussed later in the paper. In the western U.S. "turquoise" commonly occurs as nuggets, veins, crusts and inclusions in altered rhyolite or trachyte volcanic rocks.

Planerite

The ideal formula for planerite is "A"$Al_6 (PO_4)_2 (PO_3OH)_2 (OH)_8.4H_2O$. The A site in pure planerite is vacant, but usually contains Cu and Fe^{2+} which gives the mineral a light blue to blue-green color to grayish-green colors. It commonly occurs as bortyoidal crusts and veins and, in the western U.S., is associated with copper deposits as a secondary mineral. The planerite reported on in this study is a copper rich planerite from the Cripple Creek, Colorado area that was sold as turquoise.

Faustite

Faustite is the Cu, Zn analog of turquoise and ranges in color from various shades of green to bluish-gray to gray. It occurs much like “turquoise” in nodules, veins and crusts, often associated with “turquoise” in deposits at Carico Lake, Lander County, Nevada. A “turquoise” faustite specimen was obtained from a dealer. X-ray and chemical analysis of this sample showed it to be a mixture of turquoise, kaolinite clay, chrysocolla and alunite. Two specimens also purchased as turquoise proved to be faustite through x-ray and chemical analyses. These samples were from Kingman, Arizona and Lander County, Nevada.

Coeruleolactite

According to Foord and Taggert (1998), the existence of this member is doubtful. They base this on the supposed Ca content of coeruleolactite because the ionic radius of Ca^{2+} is much larger than Cu, Zn or Fe^{2+} and making the formation of a mineral with this composition unlikely. The mineral was originally described as having a white to bluish color occurring as veinlets, crusts and bortyoidal aggregates. Numerous samples of coeruleolactite were examined by Foord and Taggert and all were found to be cuprian planerite, turquoise-planerite or a mixture of variscite and wavellite.

Dark olive green to blue green samples from the Royalston District, Lyons County, Nevada were thought to be coeuruleolactite but were found to consist of material intermediate between planerite and chalcosiderite. Coeruleolactite will not be discussed in this paper because of its questionable status in the turquoise group.

Aheylite

This mineral is thought to be the ferroan analog of turquoise and faustite. Zinc is usually the major cation present along with Fe^{2+}. It ranges in color from pale blue to blue-green and occurs as bortyoidal aggregates and clumps.

Chalcosiderite

Chalcosiderite is the Fe^{3+} end member of the turquoise group. Copper is the primary cation with some Al^{3+} substituting for Fe^{3+}. The color ranges from siskin-green to dark green. It was found at Bisbee, Arizona as crusts and massive pieces with good conchoidal fracture. It also occurs as a secondary mineral in some copper deposits in the western U.S. In Nevada it occurs with “turquoise” in Lyon and Lander Counties.

ANALYTICAL METHODS

The cations Cu, Zn, Fe, Al, P and Ca were determined on small, hand picked samples broken off from larger specimens. Approximately 1 to 3 grams were separated for chemical and x-ray analyses. Chemistry was done using the ICP technique. The samples were fused with a mixture of lithium tetraborate/lithium metaborate at 1050°C. The melt was then dissolved in 100mL solution containing 5mL HNO_3. After dissolving and cooling, the solution was diluted to 250mL with deionized water and 5mL concentrated HCl. The samples were then further diluted by 2 and analyzed for Cu, Zn, Fe, Al, P and Ca by ICP-OES using matrix matched standards. Si content was monitored to identify samples for high levels of Si. Fused lithium borate blanks were used for matrix matching the standards, also containing the same concentrations of HNO_3 and HCL. Three samples were analyzed using a Bausch & Lomb solid-state XRF unit.

X-ray diffraction scans were done using a Norelco-Phillips diffractometer with settings at 40Kv and 30ma, Cu K alpha1 radiation. Scans were made from 8° to 65° two theta at a step increment of 0.02° and a dwell of 2 seconds. Each sample was run two times and peak intensities and positions averaged.

SAMPLES EXAMINED

A total of 30 "turquoise" specimens from the western U.S. were tested along with 5 samples of variscite from Utah, Nevada and Australia. X-ray diffraction scans were made on 20 of the "turquoise" samples and all 5 samples of variscite. Chemical analyses were obtained on 19 of the "turquoise" samples. Shown in Table 2 are the localities of all the samples examined together with those that were tested by x-ray diffraction and chemical analyses.

Variscite specimens were included in the testing for comparative purposes. Variscite resembles turquoise in color and is beginning to appear more often as a "turquoise" gem stone.

All of the samples were either collected by the author or purchased from various sources such as eBay and rock shops.

Table 2. Samples examined.

Locality		Chemical Analyses	X-Ray Diffraction
Arizona			
	Pearce, Cochise Co.	X	X
	Kingman, Mojave Co.	X	X
	Kingman, Mojave Co.	X	----
	Kingman, Mojave Co.	X	----
	Bisbee, Cochise Co.	----	X
	Turquoise Mtn., Mojave Co.	X	----
	Turquoise Mtn., Mojave Co	X	X
	Turquoise Mtn., Mojave Co.	----	----
	Sleeping Beauty, Gila Co.	X	X
	Sleeping Beauty, Gila Co.	----	X
	Sleeping Beauty, Gila Co.	----	X
	Sleeping Beauty, Gila Co.	----	X
	Sleeping Beauty, Gila Co.	----	----
	Morenci, Greenlee Co.	----	----
Colorado			
	Cripple Creek, Teller Co.	X	X
New Mexico			

	Hachita, Hidalgo Co.	X	X
	Hachita, Hidalgo Co.	----	----
	Cerrillos, Santa Fe Co.	X	X
	Cerrillos, Santa Fe Co.	X	----
	Cerrillos, Santa Fe Co.	X	----
	Oro Grande, Otero Co.	X	X
	Oro Grande, Otero Co.	X	X
Nevada			
	Carico Lake, Lander Co.	X	X
	Fox Mine, Lander Co.	X	X
	Fox Mine, Lander Co.	X	----
	Fox Mine, Lander Co.	----	X
	#8 Mine, Eureka Co.	X	X
	#8 Mine, Eureka Co.	----	----
	Pilot Mtn., Esmeralda Co.	----	X
	Pilot Mtn., Esmeralda Co.	----	X

ANALYTICAL DATA

The results of the chemical and x-ray analyses are given in Tables 3 and 4 respectively. Every effort was made to submit pure samples of each specimen for both the chemical and x-ray analyses.

Table 3. Chemical analyses of the turquoise group.

Sample	CuO	ZnO	CaO	Fe_2O_3	Al_2O_3	P_2O_5	H_2O	SiO_2
1.	9.78	___	___	____	37.60	34.90	17.72	____
2.	___	___	___	____	40.68	37.76	21.56	____
3.	1.74	7.90	___	____	37.13	34.46	18.59	____
4.	___	___	___	8.92	37.96	35.23	17.89	____
5.	8.06	___	___	48.56	____	28.77	14.61	____
6.	0.91	0.11	0.05	0.16	37.10	34.90	____	<5
7.	8.24	0.04	0.17	3.30	33.20	37.76	____	<5
8.	5.81	0.04	0.02	1.28	28.40	25.60	____	<5
9.	2.62	4.64	0.14	2.21	34.50	32.40	____	<5
10.	8.30	0.02	0.02	1.01	38.60	36.10	____	<5
11.	5.84	0.06	0.10	1.55	31.90	40.90	____	<5
12.	4.14	0.16	2.39	1.11	27.10	16.80	____	15-20
13.	4.07	0.20	0.41	1.17	24.30	17.80	____	10-15
14.	4.39	4.87	0.47	4.11	26.00	25.70	____	15.8
15.	3.95	0.27	0.10	2.68	24.40	23.40	____	<5
16.	7.51	0.36	0.50	5.91	25.70	19.80	____	19.1
17.	10.2	___	0.30	3.09	29.30	28.30	____	6.60
18.	5.96	0.02	0.12	3.48	25.50	23.60.	____	<5
19.	4.85	0.94	1.69	1.02	25.40	19.60	____	15-20
20.	5.73	0.12	0.68	2.60	28.00	19.80	____	15-20
21.	4.89	0.04	0.36	3.97	24.60	19.00	____	15-20
22.	3.73	0.13	2.00	3.10	24.70	18.40	____	15-20
23.	8.81	0.14	___	0.28	37.70	34.50	18.20	____

1. Ideal Turquoise
2. Ideal Planerite

3. Ideal Faustite
4. Ideal Aheylite
5. Ideal Chalcosiderite
6. Planerite, greenish-blue, Cripple Creek, Teller Co., CO.
7. Turquoise, dark sky -blue, Pearce, Cochise Co., AZ
8. Turquoise, dark bluish-green, Hachita, Hidalgo Co., NM
9. Turquoise (Faustite), light greenish-blue, Kingman, Mojave Co., AZ
10. Turquoise, dark sky -blue, Kingman, Mojave Co., AZ
11. Turquoise, light sky-blue, Kingman, Mojave Co., AZ
12. Turquoise, greenish-blue, #8 Mine, Eureka Co., NV
13. Turquoise, light blue, Fox Mine, Lander Co., NV
14. Turquoise (Faustite), light blue, Fox Mine, Lander Co., NV
15. Turquoise, light blue-green, Turquoise Mtn., Mojave Co., AZ
16. Turquoise, dark greenish-blue, Turquoise Mtn., Mojave Co. AZ
17. Turquoise, sky -blue, Sleeping Beauty Mine, Gila Co., AZ
18. Turquoise, greenish-blue, Oro Grande, Otero Co. NM
19. Turquoise, light sky -blue, Oro Grande, Otero Co. NM
20. Turquoise, dark sky- blue, Cerrillos, Santa Fe Co., NM
21. Turquoise, sky- blue, Cerrillos, Santa Fe Co., NM
22. Turquoise, greenish- blue, Cerrillos, Santa Fe Co., NM
23. Turquoise, Lynch Station, Virginia. New Analysis by Foord and Taggart(1998)

Note: Quartz (SiO_2) content estimated based on internal standard on XRD scans and from chemical analyses monitoring of the Si content.

Table 4. Chemical average and range in composition of western U.S. turquoise.

CuO	5.95%	3.7% to 10.2%
ZnO	0.17%	0% to 0.9%
CaO	0.63%	.02% to 2.4%
Fe_2O_3	2.52%	1.0% to 5.9%
Al_2O_3	27.94%	24.3% to 38.6%
P_2O_5	24.78%	16.7% to 40.9%
SiO_2	10.6%	<5% to 20%

Chemical Analyses Results

Shown in Table 3 are the published analyses of the ideal composition for turquoise, planerite, faustite and chalcosiderite together with 17 analyses of western U.S. “turquoise”. Sample #23 in Table 3 is the chemical analysis of the turquoise from Lynch Station, Virginia.

As seen from the chemical analyses, there is not “pure” western U.S. turquoise such as that from Virginia. They all contain varying amounts of Cu, Zn, Ca and Fe in the A site. The composition of the U.S. turquoise samples shown in Table 4 range from 3.7 percent up to 10.2 percent CuO, up to almost 1 percent ZnO, up to 2.4 percent CaO, from 1 percent to almost 6 percent Fe_2O_3, 24 percent to 39 percent Al_2O_3 and 17 percent to 41 percent P_2O_5. Silica, as quartz, is the most common impurity, ranging from less than 5 percent up to 20 percent. The other mineral impurities commonly found associated with low grade turquoise is kaolinite. The high CaO in samples #12 and 22 is calcite. The primary x-ray reflection for calcite is 3.09 which is masked by the 3.09 turquoise peak.

The presence of quartz in a turquoise deposit or sample is important as the silica tends to make the turquoise harder, more compact and thus giving it more durability and polish.

The chemical data does not clearly suggest any significant impact by the presence of Fe on color. Sample #16 from the Turquoise Mountain Mine, Mojave County, Arizona has the highest Fe2O3 content of 5.91 percent and does have a dark greenish-blue color, but other samples with iron content over 3 percent have no greenish hues, such as the sample from Cerrillos, New Mexico (#21) with a Fe_2O_3 content of 3.97 percent which has a light sky-blue color. This suggests that the effect of iron on the color in turquoise is dependent on the site of the Fe in the turquoise structure.

A specimen from the Fox Mine, Lander County, Nevada shows color zoning on a polished surface from sky-blue to light sky-blue. This color zoning is caused by the migration of Cu from the darker blue part to less Cu in the lighter blue area. Generally turquoise with a greenish hue would indicate Fe while blue hues have higher Cu content. As shown in Table 3, however, the presence of Fe or the Cu/Fe ratio can still produce a mostly blue turquoise. This indicates that the Fe in a blue turquoise is Fe^{3+} and has probably replaced some aluminum in the Al^{3+} site. Iron occurring as Fe^{2+} replacing Cu^{2+} will have a more profound effect on the color depending on the Cu^{2+}/Fe^{2+} ratio.

X-Ray Diffraction Results

X-ray data is given in Table 5. Also shown in this table is the comparative x-ray data for turquoise from the Lynch Station, Virginia type locality along with diffraction data for planerite, faustite, aheylite and chalcosiderite. Only the highest intensity peak reflections are listed for each of the samples examined.

Table 5. X-ray diffraction data for turquoise mineral group.

1. Chalcosiderite		2. Aheylite		3. Faustite		4. Planerite		5. Cu Planerite		6. Cripple Creek		7. Frerrian Turquoise	
d	I	d	I	d	I	d	I	d	I	d	I	d	I
----	----	9.00	10	9.03	50	----	----	----	----	----	----	----	----
----	----	6.68	15	6.70	70	6.80	90	6.78	45	6.82	80	----	----
6.38	60	----	----	----	----	----	----	----	----	----	----	----	----
6.15	20	6.14	45	6.14	70	6.18	30	6.20	30	6.18	50	6.22	40
----	----	5.97	20	5.98	40	----	----	6.04	10	----	----	----	----
4.91	25	----	----	----	----	----	----	----	----	----	----	----	----
----	----	4.79	20	4.81	50	4.72	35	4.77	25	4.73	50	4.83	50
4.58	15	----	----	----	----	----	----	4.61	10	----	----	----	----
3.76	100	----	----	----	----	3.74	100	----	----	3.75	100	----	----
----	----	3.67	100	3.68	100	3.69	60	3.69	100	----	----	3.70	100
3.52	40	----	----	----	----	----	----	3.50	15	----	----	----	----
3.37	50	3.43	40	3.44	60	3.43	25	3.43	45	3.43	40	3.46	70
----	----	3.27	40	3.28	60	3.29	35	3.28	45	----	----	3.31	70
3.00	75	3.07	20	3.08	40	3.09	35	3.09	45	3.09	30	----	----
2.95	45	2.91	35	2.92	60	2.93	20	3.01	10	2.93	25	2.93	90
----	----	2.89	70	2.89	80	2.89	15	2.89	55	2.86	25	2.91	70
2.52	10	2.52	20	2.52	40	2.51	25	2.53	20	2.51	30	2.54	40

8. Turquoise	9. Pearce	10. Hachita	11. Kingman	12. #8 Mine	13. Fox Mine

d	I	d	I	d	I	d	I	d	I	d	I
8.98	20	9.03	10	9.02	10	8.94	10	9.04	10	9.03	10
6.70	35	6.72	35	6.72	30	6.68	10	6.72	30	6.74	25
----	----	----	----	----	----	----	----	----	----	----	----
6.17	75	6.17	75	6.16	60	6.16	30	6.18	50	6.16	50
5.99	45	5.99	45	6.00	35	5.97	35	6.00	10	6.00	25
----	----	----	----	----	----	----	----	----	----	----	----
4.79	45	4.80	40	4.78	40	4.79	35	4.80	30	4.81	25
----	----	----	----	----	----	----	----	----	----	----	----
----	----	----	----	----	----	----	----	----	----	----	----
3.69	100	3.68	100	3.67	100	3.67	100	3.68	100	3.67	100
----	----	----	----	----	----	----	----	----	----	----	----
3.43	45	3.43	45	3.43	60	3.43	50	3.44	50	3.43	40
3.26	25	3.27	35	3.27	15	3.27	20	3.27	40	3.27	30
3.08	25	3.08	20	3.08	15	3.08	10	3.10	20	3.09	25
2.90	80	2.90	85	2.90	90	2.89	60	2.91	80	2.90	80
2.87	20	----	----	----	----	----	----	----	----	----	----
2.51	30	2.51	25	2.51	20	2.51	20	2.52	20	2.52	15

14.		15.		16.		17.		18.		29.		20.	
Sleeping B		Sleeping B		Sleeping B		Sleeping B		Oro Grande		Cerrillos		Turq. Mtn.	
d	I	d	I	d	I	d	I	d	I	d	I	d	I
9.07	10	8.98	10	8.89	10	8.88	10	9.00	10	8.88	10	8.85	10
6.72	20	6.72	10	6.68	20	6.68	20	6.73	20	6.64	15	6.70	25
----	----	----	----	----	----	----	----	----	----	----	----	----	----
6.17	45	6.17	90	6.12	40	6.14	40	6.19	40	6.15	40	6.16	60
6.00	25	6.00	10	5.93	20	5.95	20	5.99	20	5.92	15	5.94	20
----	----	----	----	----	----	----	----	----	----	----	----	----	----
4.80	30	4.79	10	4.74	25	4.77	30	4.80	25	4.75	25	4.72	20
----	----	----	----	4.59	10	----	----	----	----	----	----	----	----
----	----	----	----	----	----	----	----	----	----	----	----	----	----
3.68	100	3.68	100	3.65	100	3.66	100	3.68	100	3.65	100	3.68	100
----	----	----	----	3.46	10	----	----	----	----	----	----	----	----
3.43	60	3.43	30	3.41	50	3.41	45	3.43	45	3.41	40	3.41	41
3.27	35	3.28	25	3.25	30	3.27	35	3.29	35	3.26	35	3.24	30
3.09	20	3.09	20	3.07	20	3.07	20	3.09	15	3.07	15	3.08	10
----	----	----	----	----	----	----	----	----	----	----	----	----	----
----	----	----	----	----	----	----	----	----	----	2.94	10	----	----
2.90	90	2.90	60	2.89	90	2.89	40	2.90	85	2.89	90	2.88	80
2.52	20	2.52	20	2.50	10	2.51	15	2.52	15	2.51	15	2.52	15

1. Chalcosiderite, PDF card # 37-446
2. Aheylite, PDF card # 50-1653
3. Faustite, PDF card # 06-0216
4. Planerite, PDF card # 50-1654
5. Cu-Planerite, PDF card # 47-1489
6. Planerite, bluish-green, Cripple Creek, Teller Co., CO.
7. Ferrian Turquoise, Gaines, etal, (1997)
8. Turquoise, Lynch Station, Virginia
9. Turquoise, dark sky-blue, Pearce, Cochise Co., AZ
10. Turquoise, dark bluish-green, Hachita, Hidalgo Co., NM
11. Turquoise, light sky-blue, Kingman, Mojave Co., AZ
12. Turquoise, greenish-blue, # 8 Mine, Eureka Co., NV
13. Turquoise (Faustite) light blue, Fox Mine, Lander Co. NV
14. Turquoise, dark blue, Sleeping Beauty Mine, Gila Co., AZ

15. Turquoise, light blue, Sleeping Beauty Mine, Gila Co., AZ
16. Turquoise, greenish-blue, Sleeping Beauty Mine, Gila Co., AZ
17. Turquoise, sky-blue, Sleeping Beauty Mine, Gila Co., AZ
18. Turquoise, greenish-blue, Oro Grande, Otero Co., NM
19. Turquoise, dark sky-blue, Cerrillos, Santa Fe Co., NM
20. Turquoise, light blue-green, Turquoise Mountain, Mojave Co., AZ

Two "turquoise" samples from Pilot Mountain Mine, Esmeralda County, Nevada had x-ray scans showing a mixture turquoise and conichalcite, $CaCu\,(AsO_4)\,OH$. The sample from Bisbee, Arizona was brochantite, $Cu_4\,(SO_4)\,(OH)_6$. The sample from Carico Lake, Lander County, Nevada turned out to be a mixture of chrysocolla, kaolin, alunite and turquoise. All of these samples were obtained as turquoise from mineral dealers on eBay.

The turquoise group minerals aheylite and faustite have almost identical x-ray patterns when compared with the turquoise from Virginia (sample #8, table 5). The three major reflections were identical to turquoise with the only real differences in the relative intensities of the peaks. Planerite also matched the turquoise x-ray scan but with two big exceptions. The location of the major peak for planerite is at 3.74 and not 3.69 as it is for turquoise. The other difference is the absence of the 010 reflection site (8.98) in planerite. Chalcosiderite is the only other turquoise group mineral with a distinctive x-ray scan.

The samples were selected for x-ray analyses based on their colors in order to determine what effects color would have on the on the structure. There were some minor shifts caused by low Cu, high Fe^{2+} and /or Fe^{3+} on the higher d spacings for samples which had higher Cu and Fe contents, but these were not considered significant. The color/chemical composition has very little effect on the x-ray scans. Two samples in Table 5 are turquoise group minerals. Sample #6 from Cripple Creek, Colorado is planerite and sample #13 from Kingman, Arizona is faustite. The faustite scan is very close to that of the Virginia turquoise while the planerite pattern closely fits the planerite standard scan #4. These samples were also obtained as "turquoise".

DISCUSSION OF THE TURQUOISE GROUP MINERALS

Foord and Taggart (1998) make an argument that bright blue or blue-green turquoise from most world-wide localities are actually planerite, not turquoise and that the only true turquoise is from the Bishop Mine, Lynch Station, Campbell County, Virginia.

Planerite, as discussed earlier, in its purest chemical state has the A site completely vacant. Because of this there is no d(010) reflection at about 9.0 angstroms as shown in Table 5, #4. Turquoise however, because the A site is filled, has a well-defined d(010) peak. This and the location of the primary peak at 3.74 angstroms are the two main differences between the two x-ray patterns.

Foord and Taggart go on to say that a complete solid-solution series exists between planerite and turquoise and that most of the turquoise described in the literature is actually planerite. They also suggest that a complete solid-solution series occurs between faustite and turquoise. Examination of the chemical analyses in Table 3 shows that the sample from Cripple Creek, Colorado is planerite with a very small portion of the A site filled with Cu and Zn. The x-ray pattern also fits for planerite. All the other samples appear to be turquoise from the x-ray data. But there are two samples which were shown to be faustite strictly from the chemical analyses. The samples from Kingman, Arizona and the Fox Mine, Lander County, Nevada contained 4.64 percent ZnO and 4.87 percent ZnO, respectively.

The highest CuO content for a western U.S. turquoise is 10.2 percent, which is almost the same amount calculated for ideal turquoise (9.78 percent) (samples #1, #17; table 3). This material is from the Sleeping Beauty Mine, Gila County, Arizona. It is light sky blue and has a Fe_2O_3 content of 3.09 percent all of which probably substitutes for an equal amount of the Al_2O_3. The other samples with high CuO is one from Kingman, Arizona with 8.30 percent and from Pearce, Arizona with 8.24 percent, (samples #10, #7, respectively; table 3). Again, if most of the Fe in these two samples replaces some of the Al, then the formula's for these two closely approach the "true" turquoise from Virginia. The x-ray scans for all three of these samples are almost identical to the Virginia material.

The x-ray diffraction data shown in Table 5 indicates that all of the western U.S. turquoise samples have identical scans, with very little differences in d spacing and intensity when compared with the scans for the Virginia turquoise.

CONCLUSIONS

The data accumulated in this investigation suggests that in some cases, a solid- solution series could exist between turquoise and planerite but on a much smaller or restricted scale. Most western U.S. turquoise is close to the turquoise from Virginia as far as the x-ray diffraction data is concerned. Chemically, most of the western U.S. turquoise varies widely from the Virginia material in the relative amounts of CuO, Al_2O_3 and P_2O_5. Still there are three western U.S. samples that could be equated to the one "true" Virginia turquoise. The real difference however, is the amount of SiO_2 found in the western U.S. samples. Most likely all these variations in the chemistry of these samples is due more to the environment in which they were formed and the more abundant reservoir of the various cations which could enter the A site in the turquoise structure rather than a solid-solution series.

Should all western U.S. "turquoise" be called planerite? The data implies that this is not the case. Turquoise samples from the same mine or locality were found to vary widely in chemistry and color, such as the samples from Kingman, Arizona (samples #9, #11; table 3). If these were all originally planerite, how can you explain the wide range in CuO content from 2.62 percent to 8.30 percent with one having a ZnO content of 4.64 percent, which would make that sample (#9) faustite and related to the two turquoise samples? Could this be a solid-solution series between faustite and turquoise, or did the ZnO simply "join" the CuO in the A site of that one particular sample? The other interesting thing about the possible faustite sample from Kingman is its color, light greenish-blue, which suggests that most of the 2.21 percent Fe_2O_3 is also in the A site with the ZnO and the CuO. Three samples from Cerrillos, New Mexico (#21 to #23), also varied in CuO from 3.73 to 5.73 and in color from sky-blue to greenish blue.

TURQUOISE FACSIMILIES

Imitations of turquoise consist of two types, synthetic and other natural minerals which resemble turquoise in durability and color. Synthetic materials, most of which are coming from China, usually are plastic, glass, ceramic or dyed minerals such as howlite and magnesite. Sophisticated synthetics consist of plastic bonded material laced with copper salts and sintered ceramics containing copper and aluminum. Fortunately these are more common in Europe than in the U.S. A dangerously close synthetic turquoise with uniform color and even a spider-web veined matrix does occur in the U.S. These synthetics are chemically perfect and look natural in hardness and color. Pyrite is even added for realism. Most of this material is being imported from China and is difficult to distinguish without a x-ray diffraction scan.

There are naturally occurring minerals which are being offered as turquoise or turquoise related gem stones. The more common ones are chrysocolla, chrysoprase, variscite, and gaspeite (table 6). When the color of these minerals are very similar to turquoise, only chemical or x-ray analyses will give there true identity.

Table 6. Turquoise facsimiles.

Chrysocolla	$Cu_2 H_2 (Si_2O_5) (OH)_4$	
Chrysoprase	SiO_2 (Ni)	
Variscite	$Al PO_{4.} 2H_2O$ (Cr^{3+}, Fe^{3+})	Orthorhombic
Metavariscite	$Al PO_4.2H_2O$ (Cr^{3+},Fe^{3+})	Monoclinic
Gaspeite	$(Ni,Mg,Fe) CO_3$	
Chinese "turquoise"	non-mineral	

Chrysocolla

This is the most common imitator of turquoise. Chrysocolla, $Cu_2 H_2 (Si_2O_5) (OH)_4$, is blue to blue green and is found in most copper deposits as a secondary mineral. It has been used as a semi-precious gem stone almost as long as turquoise. It is often seen in old Native American pawn jewelry along with turquoise. Today it is probably the most common natural substitute for turquoise.

Chrysoprase

Chrysoprase is chalcedony quartz which contains disseminated nickel silicate which gives it a apple-green to pale green color. This is an attractive semi-precious stone and has also been around for a long time, but as high grade natural turquoise is becoming more expensive, chrysoprase is beginning to appear as a turquoise imitator. Most of the good chrysoprase now comes from Australia with California as the leading U.S. source.

Variscite

This is a fairly rare semi-precious stone which often demands higher prices than some turquoise. Variscite is also a phosphate mineral like turquoise with a formula $AlPO_4.2H_2O$. Minor substitution of Cr^{3+} and Fe^{3+} for Al gives variscite the appealing pale green to blue-green to dark green colors. The most desirable material comes from the Clay Canyon deposit, Utah County, Utah. Another Utah source currently producing good variscite is from Lucin, Box Elder County Lately variscite has been showing up from northern Nevada. This material is completely different than the Utah variscite in that it tends to be more bluish-gray to light bluish-green colors and not as hard. Some of the Nevada material will have a spider-web matrix much like some turquoise. The Nevada variscite probably contains some copper which gives them the bluish color and because of this they are more often "confused" with turquoise.

Probably the best, semi-precious gem quality variscite seen today is from Australia. This material is very hard and has deep vivid apple-green to emerald green color. This variscite has not made an impact as yet in the U.S.

X-ray diffraction scans on variscite from Utah, Nevada, Idaho and Australia showed them to all contain varying amounts of the monoclinic variety metavariscite and the orthorhombic variscite. The Nevada spider web variscite, which demands a high price, was all metavariscite and krohnite, $NaCu^{2+}(SO_4)_2.2H_2O$.

Gaspeite

Gaspeite is a nickel magnesium iron carbonate from Australia. It occurs as a secondary mineral associated with Ni sulfide deposits north of Perth (Nickel, 1973). The color ranges form a bright grass-green to olive-green to pale green and because of its hardness takes a very high polish. Gaspeite is probably the most expensive turquoise-like semi-precious gem stone seen today. It first found its way into the turquoise related markets about 10 years ago when it began to show up in Santa Fe. At that time it was passed off as a “new green turquoise from Nevada”. Later, as its popularity increased it became gaspeite from Australia.

Aside from chrysocolla, gaspeite is the only other non-turquoise mineral which is commonly found in jewelry crafted by Native Americans in the southwest. It generally demands a higher price than most turquoise jewelry.

TURQUOISE MARKETABILITY

A hundred years ago turquoise in the U.S. was found primarily in Arizona and New Mexico with lesser amounts in Colorado and Nevada. All of it was high grade natural turquoise primarily crafted into jewelry by Native Americans. Today most of the turquoise in jewelry in the southwest is still made by Native Americans but the quality has long since disappeared. Most of the turquoise being mined at the present time comes from deposits in Nevada and Arizona. Very little is produced in New Mexico and practically none in Colorado. Almost all of this material is treated in some way to enhance hardness, durability and color. The small amount of natural untreated turquoise mined from the above states commands a higher price.

Color is still the primary indicator of the value of a turquoise stone. The most desirable colors are strong sky-blue to “robin’s egg” blue. The value decreases with the increase of green hues, lighter colors, mottling and matrix. The exception is turquoise with a “spider web matrix”. This material, in its natural state, demands a high price because of its rarity and attractiveness.

Treatments

Turquoise is treated to enhance both color and durability. Durability is important as it increases the hardness and decreases the porosity, which allows the stone to take a high polish. The first early treatments were oiling and light waxing to enhance the color, but this was only effective on turquoise that was high grade and naturally hard. Over the years as high grade turquoise became scarce, waxing and oiling was replaced by pressure impregnation of the softer material by epoxy resins. This treatment, which is called stabilization, is in common use today. As we will see later, over 60 percent of all the turquoise mined today is stabilized. Without this treatment, there would be no turquoise markets.

The stabilization of low to medium grade turquoise is not a bad thing. Stabilized turquoise will retain its luster and color and becomes just as durable as high grade natural turquoise. Most important is that stabilized turquoise has not been altered. The pores in the stone have simply been filled with a clear resin. X-ray diffraction scans were run on natural un-stabilized and stabilized turquoise from Oro Grande, New Mexico, Fox Mine turquoise from Lander County, Nevada and turquoise from the Sleeping Beauty Mine, Gila County, Arizona. All three samples had the same x-ray pattern for turquoise on both the natural and stabilized material with no d spacing or line intensity shifts. Chemical analysis was run on a stabilized Oro Grande sample with no difference from the un-stabilized sample.

The most extreme treatment and one now finding its way into the U.S. market from China is "re-constituted" turquoise. Fragments of natural turquoise too small to set in jewelry are ground into fine powder and then bonded to form a solid stone. This material is then dyed to enhance the color. The finished product takes a very high polish and can be formed into many different shapes. The high luster on the "turquoise" often sets it apart from the more "dull" natural turquoise shine.

Grading of Turquoise

The grading of turquoise is, at best, subjective. Probably the best criteria put forth so far is that by Lee Anderson (2006).

Gem

This turquoise stone must be perfect in color and durability with a natural luster which comes from within the stone and not just from a surface polish. Less than 1 percent of all turquoise can be called "gem".

Very High Grade

This is nearly perfect turquoise but the matrix pattern may not be as balanced as in the gem category. This turquoise will still be hard and lustrous. About 3 percent of all turquoise is very high grade.

High Grade

Turquoise of this grade is used in most of the high end quality jewelry. It is not as hard as the very high grade type, but still would not require any stabilization. It still would have the perfect luster. About 5 percent of turquoise fits this grade.

Jewelry Quality/High Quality

This turquoise should have a good hardness, color and luster. The matrix pattern is attractive but not over dominant. This stone could be stabilized but doing so would be unnecessary. About 10 percent of turquoise is in this grade.

Mine Run/Average Quality

This is average turquoise that usually does not require stabilization as it holds its polish and luster for a limited time. Stabilization, however, improves the durability and color and produces a much more desirable stone for the market place. An estimated 20 percent of turquoise is this grade.

Chalky/Bulk/Common

The turquoise in this grade is soft, porous and brittle and of little value until it is stabilized. Usually stones of this type have light color hues and stabilization will slightly improve the color, durability and luster. On rare occasions the color may be enhanced by artificially coloring. Most mined turquoise today from the western U.S. falls into this category, which makes up about 60 percent of mined turquoise.

As you can see from the above, between 60 and 80 percent of all the turquoise mined today, primarily from Nevada and Arizona is stabilized. The price per gram increases significantly for the 20 to 40 percent which requires no treatment.

The bottom line is that untreated turquoise with good color and durability will also command the higher price. Stabilized turquoise, although the "standard" in today's market, will be priced less. Fabricated turquoise imitations are priced considerably less and are commonly found in the costume jewelry departments.

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Poster Abstracts

EVOLUTION OF THE LANDSCAPE ALONG THE CLEAR CREEK CORRIDOR, COLORADO—URBANIZATION, AGGREGATE MINING, AND RECLAMATION

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In the semiarid climate of the Colorado Front Range, flood plains along major streams provided prime agricultural land that supported settlement of the region. Clear Creek, between Golden, Colorado, and its confluence with the South Platte River was one such stream. The discovery of gold in the alluvial deposits of Clear Creek spurred an additional interest in the flood plain. But the demand for sand and gravel for construction purposes initiated a sequence of events that exceeded previous interests in the flood plain and created the modified landscape and urban ecosystem that exists along Clear Creek today. The Denver metropolitan area in general, and the Clear Creek corridor in particular, provide illustrative examples of the effects of sand and gravel mining on an area over time. The valley corridor offers a landscape filled with a persistent visible and hidden reminder of its past use.

Mining is a necessary step in the ongoing process of development, and it is important to recognize the inevitable change of landscapes associated with the process. The evolution of the Clear Creek landscape is analyzed as a series of compositions, both at the macro view (in the spatial context of urban structure and highways from aerial photographs) and micro view (from the civic scale where landscape features like trees, buildings, and sidewalks are included). Four types of reclaimed mine pits are repeated in various locations along Clear Creek: "hidden scenery," water storage facilities, wildlife/greenbelt space, and multiple-purpose reservoirs. Six sites are selected to illustrate the evolution of past land use and reclamation. Since the South Platte River and its other major tributaries are still undergoing this evolutionary process, the results of this investigation may be useful in under-standing and planning their future.

CHARACTERIZATION OF ALLUVIAL AGGREGATE DEPOSITS USING ELECTRICAL RESISTIVITY AND TIME-DOMAIN ELECTROMAGNETIC SOUNDINGS

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The U.S. Geological Survey, in cooperation with Martin Marietta Aggregates, Inc., conducted surface geophysical surveys at a site in central Indiana to demonstrate the application of geophysics for characterizing alluvial aggregate deposits. We present results from the electrical resistivity and time-domain electromagnetic (TEM) sounding methods and discuss their relation to site stratigraphy known from borehole data. The stratigraphy consists of a thick limestone and dolomite layer at depth that is overlain by 20 to 35 m of alluvial sand and gravel and 1 to 2 m of clay-rich soil at the surface. The electrical resistivity profiles accurately delineate the alluvium/limestone contact, but the TEM soundings were unsuccessful in accurately identifying this contact. The TEM data did, however, detect a shale-rich limestone layer underlying the limestone and dolomite layer. The resistivity method employed is typically stronger at resolving thin layers closer to the surface (depths of 10 m or less) than is the TEM method, whereas the advantage of the TEM method is its greater depth of penetration. These methods can be a powerful tool, particularly when used in conjunction with a drilling program, to better characterize an aggregate deposit.

MAINTENANCE OF INDUSTRIAL MINERALS TAILINGS IMPOUNDMENTS

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In the mining industry, properly functioning impoundments are crucial to effective waste management and directly influence operating costs. Failure of a dam, even a small one, can be extremely costly due to interruption of mining or mineral processing, direct costs of repair, environmental or safety fines, physical damages to downstream persons, and damage to the company's reputation in the community. A dam in disrepair poses a great risk to those living and working around it. Proper dam operation, regular maintenance, a routine inspection program, an understanding of dam performance, and a clear chain of responsibility are all necessary to ensure that an impoundment is safe and functional.

The most common means of dam failure are uncontrolled seepage through the embankment face or along the outfall pipe, uncontrolled flow over the crest, and slope failure. These failure modes can result from improper operation of the dam, such as:

- overfilling and maintaining inadequate freeboard, which can allow wave erosion of the embankment or overtopping;
- modifying the designed spillway, which may reduce capacity and allow overtopping or otherwise weaken the structure; or
- rapidly drawing down the pool, which can cause slumping of the upstream embankment face.

Failure may also result from poor maintenance and neglect, such as:

- penetration of the embankment by tree roots and animal burrows, causing leakage flowpaths and weakening the compacted fill;
- erosion of bare soil on the embankment to create a locally oversteepened slope with the potential for slumping;
- large erosion gullies that can cut through the crest;
- clogging of the outlet by rafted debris; or
- deterioration of the outlet structure allowing leakage out of the pipe and through the embankment.

To minimize the risk of dam failure, Golder recommends that a single person be clearly responsible for maintenance (and preferably operation) of the dam and impoundment. This person must have the authority and resources to routinely inspect and maintain the impoundment. A thorough dam inspection should be completed twice yearly by trained staff. During inspection, special attention should be paid to the location, flow rate, and sediment content of seepage; bare soil or eroding areas; potentially unstable or recently sloughed slopes; and the condition of the crest, spillway, and intake/outlet structures. Miners must also recognize that inspection and maintenance cannot cease when the impoundment is no longer in operation. Proper closure is necessary to minimize long-term risk of failure.

COMPARISON OF ALUNITE AND KAOLINITE MINERALIZATIONS ALONG THE NORTHERN EDGE OF SIMAV GRABEN, WESTERN TURKEY

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Several hydrothermal mineralizations occurring along the northern edge of Simav Graben, from alunite deposits of Saphane in 20 km east of to kaolin deposits of Duvertepe in 60 km west of the city of Simav, were formed in association with two different tectono-magmatic periods dominated in regional development of the Western Anatolia. During regional tectonics of the Aegean Region, the Anatolian Block moves toward the west along the “North Anatolian Fault” zone, which is a 1200 km-long left lateral strike-slip fault and the rate of western movement has reduced in the Aegean Region and caused N-S extension due to E-W compression. Firstly, the strike-slip Simav Fault trending WNW-ESE was formed by the compressive tectonic regime prevailed in the paleo-tectonic period (Cretaceous to Paleocene). Secondly, the compressive tectonic regime changed to extensional regime during Miocene to Pliocene and Simav Graben was formed due to the activation of the lateral component of the Simav Fault by N-S extension. Vein-type Pb-Zn-Cu mineralizations, which are observed along to Simav Graben, were deposited within the fractures sub-parallel to the Simav Fault. Epithermal sulfur mineralizations and hot springs occurred along the graben were formed along such transfer faults during Pliocene. These fossil geothermal fields were sulfur-rich in east, which caused of alunite mineralization and sulfur-poor, which caused of kaolin mineralization in west of the Simav Fault. Besides, the present-day silica precipitation at Ilicalar (Gediz) and hot-springs in the vicinity of city of Simav along the graben are the recent equivalents of the Miocene to Pliocene epithermal activity.

Geochemical and geochronological data reveal that the composition of volcanism changed from calc-alkaline and silicic in the Early Miocene to largely alkaline and more mafic in the Middle Miocene. Saphane alunite deposits occur as the result of hydrothermal alteration of rhyolitic-rhyodacitic tuffs along the various fault zones. The lateral alteration zones extend from inner advanced argillic to an outer propylitic-argillic zone. Vertical zoning shows silicified zone downwards through silica-alunite (alunite-kaolinite-quartz-opal-CT), limonite, and propylitic-argillic zones (K-feldspar-quartz-smectite-illite). High acid sulfate alteration caused alunite mineralization and excess silica transported upward. Fault related extensive hydrothermal alterations observed in Düvertepe kaolin deposits with minor alunite mineralization that are the products of rhyolitic tuffs and breccias and widely spreaded in both sides of the Simav Fault. Almost all economically significant kaolin deposits have been operated by various ceramic industries in the Duvertepe region.

GEOCHEMISTRY AND MINERALOGY OF BENTONITE DEPOSITS IN WYOMING AND SOUTH DAKOTA

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The variation in mineralogy and geochemistry of twenty bentonite beds are compared at the individual bed level as well as down stratigraphic section from the Cretaceous Belle Fourche and Mowry Shales of the Black Hills District, South Dakota and the Thermopolis and Mowry Shale and Frontier Formation of the Big Horn Basin, Wyoming. 231 samples were geochemically and mineralogically characterized by XRD, SEM, ICP-MS and WDXRF. Observed differences in the mineral and chemical composition vertically through the beds and stratigraphically from bed to bed reflect compositional and post depositional changes of the original volcanic ash deposits. In the Black Hills district the Clay Spur, F-Bed, Newcastle, and G-Bed were sampled. In the Big Horn Basin the Commercial, Canadian, Rusty, Beaver, Flat and numerous small bentonite beds were sampled.

The dominant clay mineral in these deposits is sodium-montmorillonite with abundances ranging from 65-90 %. Mineral grits (> 150um) analyzed by XRD shows biotite, quartz, a wide variety of Na,Ca – feldspars, potassium feldspar and Na,Ca - zeolites. Secondary minerals include vein calcite, void precipitated aragonite, blades of gypsum and clinoptilolite zeolite. Residual minerals, comprising between 0-5 wt% of the sample is derived from the original volcanic ash and post-depositional processes. The mineral abundance ratios from the grit fraction are distinctive and can be useful in differentiating the beds. Where efflorescent alkali salts on outcrop surfaces are commonly composed of sodium and calcium sulfa-salts (thenardite ($Na2SO4$), bloedite ($Na2-Mg(SO4)(H2O)4$, gypsum ($Ca(SO4)(H2O)2$, and eugsterite ($Na4Ca(SO4)3(2H2O)$).

These beds have similar mineral compositions and subtle but significant differences in the bulk geochemistry. The highest average Na concentrations were in the Flat (2.61%), Commercial (2.05%), and the Rusty (1.95%) Beds. The highest average Ca concentrations are found in the F (2.44%) and Mowry-E (1.7%) where gypsum is observed in the fine (> 100 um) and very fine (100> x >63 um) sand size fractions and the Newcastle-A (1.6%) beds, where calcite is present in the very fine sand fraction. Not surprisingly, the Rusty Bed has high average Fe (2.6%) and Mn (668 ppm) concentrations, with the Fe concentration highest in the thin 9th (3%) and the 3rd (2.6%) Beds. Individual core chemistry shows Fe-enrichment trends within the bentonite beds, increasing down core in 6 of 8 cores from the Belle Fourche F-Bed. Down core clay color variations, from bluer to more orange, correlate with these chemical trends in 4 of the 6 cores.

Discriminant Analysis based on bulk geochemical analyses predicted 17 out of 20 identified. Trace and major element geochemistry and detailed mineral characterization of these clay beds can be used to differentiate between bentonite beds of the Newcastle Sandstone, the Mowry, Belle Fourche, Thermopolis Shales, and the Frontier Formation.

SEISMIC CHARACTERIZATION OF AGGREGATE

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Seismic refraction and reflection surveys of known aggregate deposits, carried out as part of a USGS/Martin Marietta Aggregates collaborative study in 2005, provide quantitative assessments of deposit thickness and heterogeneity. Seismic tests were conducted along two transects at a site in central Indiana in order to determine the effectiveness of these geophysical techniques for augmenting borehole information and reducing the number of necessary boreholes. The compressional (P) wave seismic refraction method delineates the water table within the aggregate and the bedrock surface underlying the aggregate deposit. Shear (S) wave seismic refraction delineates the bedrock surface and shows sediment compaction due to overburden pressure at depth. Shear wave reflection shows the bedrock surface and also shows the interface between major depositional layers within the aggregate deposit, specifically a layer of gravel with some sand and a layer of sand with a trace of gravel. P-wave reflection does not prove useful at this site. Our results suggest that used together these methods (P- and S-wave reflection and refraction) can provide an assessment of geological layers that complements and extends borehole information. Shear wave methods in particular can provide a detailed characterization of aggregate deposits including total volume and major sedimentary layers.

Note: *This abstract has been prepared as a place-holder for meeting planning, but has not been reviewed for publication. The authors will happily provide an abstract suitable for publication if one is desired.*

AGGREGATE AVAILABILITY IN CALIFORNIA

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Construction aggregate is the leading non-fuel mineral commodity produced in California and the nation. Valued at $1.63 billion, it comprised about 44% of California's $3.72 billion non-fuel mineral production in 2005. Total California aggregate production in 2005 amounted to over 235 million tons, or about 6.6 tons per person. Demand for aggregate is expected to increase as California's population continues to grow and infrastructure is maintained and improved. In order to help local decision-makers plan for future availability of aggregate, the California Geological Survey (CGS) has updated Map Sheet 52 (2006), a statewide map comparing forecasted 50-year aggregate demand to permitted aggregate resources for 31 study areas throughout the state. These areas cover about 25 percent of the state and they contain approximately 4,343 million tons of permitted construction aggregate resources, supplying about 90 percent of California's population. In the next 50 years, these areas will need over 13.5 billion tons of aggregate resources, over three times the amount that is currently permitted.

Areas with very high projected aggregate demand are South San Francisco Bay, San Gabriel Valley, Temescal Valley-Orange County, Western San Diego County, and San Bernardino County. Each of these regions is expected to consume more than a billion tons of aggregate by the end of 2055. With the exception of the Yuba City-Marysville area, all of the aggregate study areas have less permitted aggregate resources than they will need for the next 50 years. Twenty-five of the 31 aggregate study areas have less than half of the permitted resources they will need. Four aggregate study areas – North San Francisco Bay, Sacramento County, Fresno County, and Northern Tulare County have less than a 10-year supply of permitted aggregate resources.

In the last five years, permitted aggregate resources have decreased by about 2.5 billion tons. Decreases are attributed to regulatory changes, new resource calculations, aggregate consumption, and social and economic conditions leading to mine closures.

Aggregate price at the plant site and transportation cost have increased significantly in the past five years. Areas throughout the state are experiencing shortages in local aggregate supply and are being forced to transport aggregate longer distances, significantly increasing the cost paid by the consumer. The shortage of PCC grade sand in the San Diego and the San Francisco Bay areas has driven up the sand price in both areas, making aggregate imports from Canada and Mexico into these regions competitive.

Information on Map Sheet 52 is intended to help planners and decision-makers balance the need for construction aggregate with the many other competing land use issues in their jurisdictions, and to provide for adequate supplies of construction aggregate to meet future needs.

ORGANIC GENESIS OF THE SULFUR OCCURRENCES AROUND ISPARTA, SOUTHWESTERN TURKEY

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The study area is located in the Alpine – Himalayan zone in Turkey. Geologically, this is very complicated region, and the rock units generally are divided into two groups as either allocthonous and autochthonous. Tectono–stratigraphically, the units are Paleozoic quartzite, black limestone, arkosic sandstone, interlaminated radiolarite and Triassic Limestone, thick Jurassic Limestone, detritic limestone, and ophiolite. Trachyte, trachyandesite, feldspathoidal trachyandesite porphyry, tuff and pumice formed by volcanism during the Plio-Quaternary also are present. Recent alluvium and slope detritus cover all the other rock units.

A number of sulfur outcrops occur in the area. Among them are outcrops at Keciborlu, Uyuzpinar, Daridere, Yakaören. The most important sulfur deposits are found in volcanic tuff and siltstone – marl, and include highly organic material. Sulfur may accumulate around recent gas diffusions and also as massive formations. The information about local geology and sulfur isotopes shows that the sulfur originated from the crust probably comes from organic – rich Paleozoic and Triassic units. The sulfur did not move between Triassic and Pliocene time. However, Plio-quaternary volcanism did cause a movement of the sulfur, and this was followed by the formation of the secondary sulfur due to post-tectonic thermal activities and the mixing of other surface waters.

EARTH MATERIALS IN MEDICINE

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The art of preparing and mixing medicines from earth materials is as old as civilization. Early man created medications by using whatever nature made available for pain, prevention, injury, and illness. Over one hundred earth materials were documented for medicinal purposes, with forty five of them being used in modern medicine. Over ninety illnesses and maladies have been treated with earth materials. They have been used for a wide range of ailments such as ice for swelling, clays and calcite for gastrointestinal problems, and pumice for cleaning stained teeth. Preparation of earth materials ranges from using them pulverized, mixed with other ingredients to using them whole, and as oil. Minerals were directly applied to the body or taken internally in various forms.The geographic distribution of uses of earth materials for healing is worldwide.

NON-DESTRUCTIVE CHEMICAL CHARACTERIZATION OF CERAMIC SHARDS FROM SHIPWRECK 31CR314 AND BRUNSWICK TOWN

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The purpose of this study is to chemically and texturally characterize ceramic oil jar shards from North Carolina shipwreck 31CR314. These shards will be compared with similar shards from Brunswick Town to explore the use of composition and texture as hallmarks. The ultimate goal would be to find the origin of the shards. The chemical components of the artifacts will be determined by environmental scanning electron microscopy/X-ray energy dispersive spectrometry (SEM/EDS) and powder X-ray diffraction. This kind of analysis is valuable for archaeological analysis because it is non-destructive to the ceramic artifacts, that is, no conductive coating is required for non-conductive specimens, as for conventional SEM. Previous studies have indicated, although not with absolute certainty, this shipwreck site to be that of *Queen Anne's Revenge*, one of Blackbeard's many ships. Analysis to date has shown that shards are compositionally similar, but Brunswick Town shards consistently contain 0.5-1.5 wt.% P_2O_5 while those from 31CR314 do not. Likewise, shards are texturally similar except for the glazed sides of all 31CR314 shards that exhibit small tracks of crescent-shaped marks not shown on shards from Brunswick Town.

GEOLOGY OF WYOMING'S INDUSTRIAL MINERALS

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Based on total value, Wyoming ranked 16th in the nation in non-fuels mineral production of soda ash, clays (bentonite), helium, cement, sand and gravel, according USGS 2004 data. Among these, Wyoming ranks first in the nation in trona and bentonite production. Other industrial minerals produced in Wyoming include flagstone, granite, gypsum, lignite and limestone. Wyoming also holds the potential to produce mineral resources such as anorthosite, industrial grade diamonds, silica sand, mineral pigment, phosphate, quartz, sulfur, travertine, and zeolite. Wyoming also hosts vast deposits of beautiful decorative and dimensional stone which are not currently produced but also have been produced, with great potential for future development as well. The geology of Wyoming's industrial minerals is extremely diverse and taps rocks from the Quaternary back to the Archaean. Wyoming has great potential to increase and diversify its industrial mineral production capacity.

INDUSTRIAL MINERALS OF COLORADO

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Colorado has a wide variety of mineral resources ranging from common sand and gravel to specialty minerals such as titanium and fluorspar. These resources are spread throughout the state, but have been developed most frequently along the heavily populated Front Range corridor in the central part of the state. In 2006, Colorado's industrial mineral production was valued at over $593 million; two-thirds of which was from the production of aggregate (sand & gravel and crushed stone). Nearly one-third of our total production value was from the manufacture of Portland and masonry cement, which is made possible through principally in-state mining of raw cement ingredients such as limestone, shale, gypsum, and silica sand. A small portion Colorado's annual industrial mineral production value is from clay, dimension stone, and specialty minerals. Clay is used primarily in the manufacture of bricks and tile products. Our dimension stone is distributed world-wide and is suitable for variety of structural, sculptural, and decorative applications. Many other industrial mineral resources are currently mined throughout Colorado. Furthermore, some historically produced commodities have the potential to make a resurgence in today's fast-growing markets. Other resources may yet be identified that will fill the markets of the future.

POTENTIAL CRUSHED STONE RESOURCES OF THE MARION, OHIO 30 X 60 MINUTE QUADRANGLE

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The Ohio Department of Natural Resources, Division of Geological Survey (OGS) has completed a map showing areas of limestone and dolomite, a potential crushed stone resource, likely covered by less than 25 feet (7.6 meters) of surficial materials in the

Marion, Ohio 30 x 60 minute (scale 1:100,000) quadrangle. The map is derived from OGS's Statewide Mapping Program, a cooperative effort with the U.S. Geological Survey begun in 1990 and finished in 1997. Primary goals of the Ohio program were to produce a statewide coverage of open-file and digital bedrock-geology, bedrock structure, and bedrock-topography maps of all 7.5-minute quadrangles (total of 788) in Ohio, leading to the first major revision of the state bedrock-geology map since 1920.

Drift-thickness maps were derived by subtracting the bedrock-topography elevations from the surface elevations. The bedrock-topography surfaces for each 7.5-minute quadrangle were drawn with interpreted 5-foot (1.5 meter) contours. Local revisions, based on historical bedrock and quarry observations and on additional data from water wells, were made to several 7.5-minute quadrangles. The 1:24,000-scale drift-thickness polygons and other features were scanned and digital lines were produced. The attributed drift-thickness polygons were combined to produce a 1:100,000-scale map and topology created in a Geographic Information System (GIS).

Bedrock geology in the Marion quadrangle ranges from the lower Silurian-age Lockport Dolomite to the upper Devonian-age Ohio Shale. Digital overlay of the 25-foot (7.6 meter) drift-thickness map with the bedrock-geology map of the Marion quadrangle shows five units that have potentially economic-quality carbonate rock occurring under thin cover. These units are, in ascending order, Lockport Dolomite, Greenfield Dolomite, Tymochtee Dolomite, Salina Group undifferentiated, and the Columbus Limestone. Most of the carbonate rocks in the Marion quadrangle are considered good to fair in quality for the production of aggregates. Crushed stone production in 2005 from the Marion quadrangle was approximately 11 million short tons (10 million metric tons).

This map is intended as a general guide to exploration or zoning for potential crushed stone resources in the Marion quadrangle. A more detailed geologic and engineering investigation should be completed before decisions are made on mining suitability of a specific site. The Marion map is a transitional derivative-mapping product. By using the comprehensive geologic GIS soon to be available at the Ohio Division of Geological Survey, future potential crushed stone resource and other derivative maps will be produced relatively quickly.

Abstracts of Additional Technical Papers (not presented orally or as posters)

GEOLOGY & GEMSTONES – WYOMING EXPLORATION MODELS

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Using traditional geological methods, dozens of gemstones have been discovered in the Wyoming Craton during the past 20 to 30 years. The geology of this region is favorable for the discovery of a variety of gemstones, some of which could lead to major discoveries and possibly to a world-class deposit.

The available geological clues in the geological and geochemical environments, have led to many recent discoveries, which have included gem-quality peridot, Cape ruby (pyrope garnet), Cape emerald (Chromian diopside), ruby, sapphire, gem-quality kyanite, diamonds, opal, jewelry-grade gold, platinum and palladium, and the largest known resources of gem-quality iolite (cordierite) in the world.

Field Trips and Guest Trips

FIELD TRIP 1

Colorado Springs cement and stone producers

Date: Sunday, May 20
Depart: 7:30 am (hotel main entrance) Return: approximately 5:00 pm
Meals: Lunch included

The first trip of the Forum will feature industrial minerals in the Colorado Springs area. Our first stop will be southwest of Colorado Springs at the Table Mountain quarry, where the highly siliceous Cretaceous Dakota Sandstone is mined for riprap, road base, aggregate, and dimension stone. Nearby, large moss-covered talus blocks of the Dakota are sold through the landscape industry as highly-sought-after decorative moss-rock.

Our second stop will be Holcim (US) Inc.'s cement manufacturing plant and quarry in Florence. Participants will be guided through Holcim's on-site quarries where limestone from the Cretaceous Fort Hays Member of the Niobrara Formation is mined as the principal raw ingredient, and the Cretaceous Codell Sandstone is mined for use as a silica additive. Pyrite nodules and fossils may be collected from spoils piles of the Niobrara Formation. The tour continues as our group is guided through the cement manufacturing plant to see the massive blending hall, corrective raw material silos, and rotary kiln. The highlight of the tour will be an open air elevator ride to the top of the pre-calcining tower where we will be treated to an aerial view of the plant and phenomenal views of the High Plains to the east and the Sangre de Cristo Range to the west.

Hardhats required, steel toed boots encouraged.

FIELD TRIP 2

Front Range aggregates

Date: Tuesday, May 22
Depart/Return Boulder: 12:00 NOON/~9:00PM (depart from hotel main entrance)
Meals: Lunch and dinner included

This trip will focus on both traditional and light-weight aggregate resources. The first stop will be TXI Operation's light-weight aggregate plant. The Cretaceous Pierre Shale is mined on site and conveyed under Highway 93 to the processing plant. Our group will follow the path of the raw material through the testing and sizing station, along the catwalk to the rotary kiln, and out to the capture silos to examine the finished product.

Stop two will visit Aggregate Industries' crushed stone operation in the small town of Morrison located right at the base of the Rocky Mountains. Precambrian granite gneiss fills a variety of crushed stone aggregate needs throughout the Front Range area. We will explore several geotechnical stability issues associated with dikes and biotite shear planes cross cutting the granite gneiss and development of the quarry in such steep mountainous terrain.

This trip will meet the concurrent spouse trip (Guest Trip C) for dinner at the world-renown Red Rocks Amphitheater. Red Rocks is a geologically formed, open-air amphitheater encircled by upturned sandstone strata in columns several hundred feet high. Red Rocks is a prime location for outdoor concerts and features breathtaking panoramic views of Denver.

Hard hats required.

FIELD TRIP 3

Northern Front Range stone producers

Date: Tuesday, May 22
Depart/Return Boulder: 12:00 NOON/~6:00PM (depart from hotel main entrance)
Meals: Lunch included

This field trip will visit three very different stone quarries near the town of Lyons (north of Boulder). Participants will see the Permian Lyons Formation (sandstone) quarried for flagstone; 1.4 billion-year-old red granite cut for dimension stone using a water jet channeler; and 60 million-year-old intrusive rocks crushed for aggregate.

Hard hats and steel-toed boots required.

FIELD TRIP 4

Clay resources and products of the Golden area

Date: Thursday, May 24
Depart/Return Boulder: 8:00AM/TBD (depart from hotel main entrance)
Meals: Lunch included

The city of Golden has a long history of clay mining. This trip will visit several historic clay pits where clay was mined to line smelting furnaces during Colorado's gold and silver boom days. The trip will also visit modern clay mines and a brick manufacturing plant in Denver. Coors Tek (formerly Coors Ceramics) will provide a tour* of one of their four facilities in Golden, where they produce a multitude of clay products ranging from basic tiles and crucibles to body armor and high-tech medical devices.

Hard hats required.

*For security purposes, non-US citizens must make reservations for this trip at least two weeks prior to the Forum.

FIELD TRIP 5

Analytical labs, stone, Yule Marble, and gypsum in Colorado

Date: Thursday, May 24 – Friday, May 25
Depart Boulder: Thursday 7:30 AM (hotel main entrance); return to Boulder Friday evening
Meals: Lunch included both days, dinner included on day one
Hard hats and steel-toed boots required.

This two day trip begins at the edge of the High Plains of Colorado, traverses several mountain ranges of the Rocky Mountains, crosses high alpine parks, and follows the Colorado River through Glenwood Canyon. We will explore mineral resource extraction, analysis and testing, and product manufacture.

***Day one**:*
The trip begins at Hazen Research's analytical lab in Golden. Hazen conducts industrial research and testing on a variety of metallic and non metallic minerals. The company was founded in 1961 by a small group of metallurgists with strong backgrounds in research and process development for the mining and chemical industries. Hazen serves clients from all over the world on projects ranging from bench-scale experiments and analyses to multimillion-dollar continuous pilot plants. Next, the trip heads south and west along U.S. Highway 285 towards Fairplay and Colorado's infamous South Park (infamous because of the TV show of the same name). We will drive through Fairplay and Alma and over Hoosier Pass to Summit County. There we will visit Everest Materials' Silverthorne sand and gravel quarry along the Blue River to see all phases of sand and gravel processing from mining to reclamation. The day ends in Glenwood Springs where we will take a tram ride up Iron Mountain, enjoy a catered dinner overlooking the Colorado River valley, and be treated to a special evening tour of the Fairy Caves. Back at the hotel, participants may spend the later part of the evening soaking in the famous Glenwood Hot Springs.

Day two:
Day two of this trip will start with a visit to the world-renown Yule Marble quarry, origin of the pure white block of marble from which the Tomb of the Unknowns was carved. The trip continues on to the town of Gypsum where we will visit American Gypsum's mine and wallboard plant. The thick deposits of gypsum mined here are from the Eagle Valley Formation, which was deposited in an arid basinal environment during Pennsylvanian time. En route, we will pass Colorado's youngest volcano (4,000 years old), which is mined intermittently for scoria.

GUEST TRIP A

Boulder sightseeing

Date: Sunday, May 20
Depart/Return Boulder: 9:00AM/4:00PM (depart from hotel main entrance)

Meals: Lunch included

This tour will visit several interesting places in Boulder and nearby Broomfield. First we will head south to the Butterfly Pavilion in nearby Broomfield to view a collection of live butterflies from around the world. After that tour we drive back to Boulder and go to the Celestial Seasonings Tea Company to tour the world famous tea factory. A snack will be provided. Nearby is the Leanin' Tree Museum and sculpture garden of Western Art. This private collection of Western Art contains an abundance of sculptures and paintings in a small museum. After that tour we drive back to downtown Boulder for afternoon tea at the Boulder Dushanbe Teahouse. This Tajikistan teahouse includes hand-carved and hand-painted ceiling, tables, stools, and columns. Visitors can enjoy high tea at the teahouse or wander down to the Pearl Street Mall to explore the uniquely diverse restaurants, shops, street performers, and beautiful mini-gardens.

GUEST TRIP B

Estes Park tour

Date: Monday, May 21
Depart/Return Boulder: 8:30AM/5:00PM (depart from hotel main entrance)
Meals: snacks (lunch on your own)

Witness the magic of the Colorado Rockies on this full day tour that leaves the cities of the Front Range far behind. The trip begins with a short hike on a handicap accessible trail around 8,710 foot high Sprague Lake with breathtaking views of the Continental Divide. We will visit the Rocky Mountain National Park Visitor's Center, followed by lunch and shopping on your own in the mountain town of Estes Park, famous for its unique architecture and intriguing shops. In lieu of shopping there is an optional horseback ride (additional $45 and reservation required email pattinewman@comcast.net). In the afternoon we will tour the historic Stanley Hotel and Stanley steamer museum. The hotel was first opened in 1909 by F.O. Stanley and is the hotel that inspired Stephen King's novel *The Shining.*

GUEST TRIP C

Denver sightseeing

Date: Tuesday, May 22
Depart/Return Boulder: 9:30AM/~9:00PM (depart from hotel main entrance)
Meals: Lunch and dinner included

This tour will head to downtown Denver to explore some of the Queen City's famous treasures. Our first stop will be the Denver Mint* to see how all our coins are made. Our lunch stop will be at the fashionable Pallete's Restaurant located in the Denver Art Museum. We will be treated to a guest speaker there, Denver Historian Tom Noel. In the afternoon we will have a tour of the Denver Art Museum and the new Frederick Hamilton Building, famous for sculpting the cornerstone of Denver's new skyline. We then head to Red Rocks Amphitheater in Morrison for a tour of the facility and a short visit to the Indian Trading Post. The trip will meet the concurrent technical field trip (Field Trip 2) for dinner at spectacular Red Rocks Amphitheater. *No cell phones, cameras, backpacks, purses, etc. allowed (wallets ok); these items will be left on the secure bus.

GUEST TRIP D

Dinoѕaur Ridge & Roxborough State Park

Date: Wednesday, May 23
Depart/Return Boulder: 9:00AM/4:30PM (depart from hotel main entrance)
Meals: Lunch included

This tour will head south along the Front Range to see the dinosaur sights around Morrison and Golden. The first stop will be Roxborough Park for a guided nature hike through the sandstone rock formations. Next will be a guided tour of the Dinosaur Ridge Natural Area to see 100 million year old dinosaur footprints. Lunch will be served at their visitor's center. After lunch we travel up to Lookout Mountain to visit Buffalo Bill's Grave site and museum. Next we drive down Lookout Mountain Road to the Coors Brewery in Golden.

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