INFORMATION SERIES 17

Geology and Resource Potential of Strategic Minerals in Colorado

by Stephen D. Schwochow
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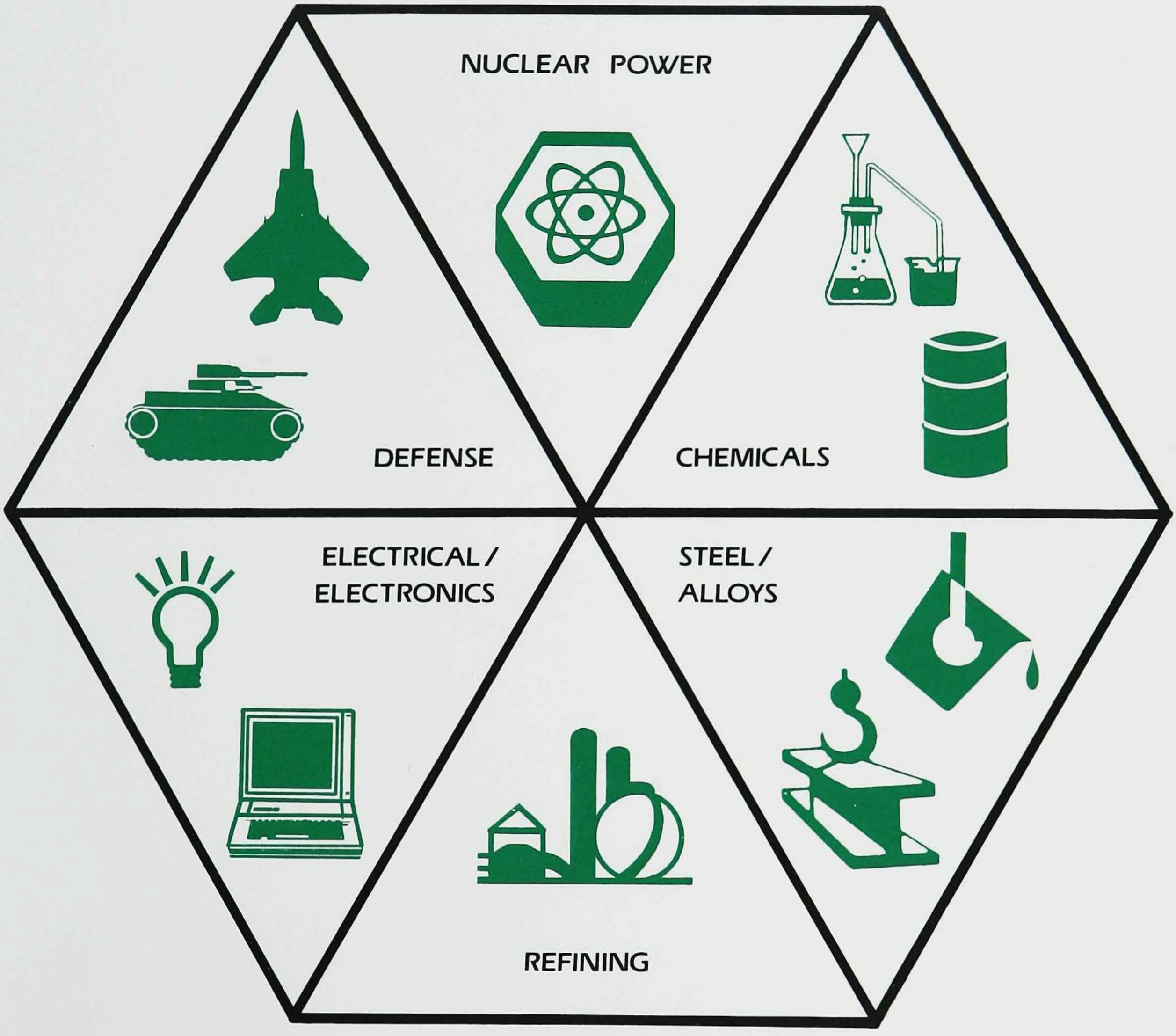

COLORADO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO / 1985

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GEOLOGY AND RESOURCE POTENTIAL OF STRATEGIC MINERALS IN COLORADO

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Colorado has huge resources of certain undeveloped strategic minerals that could supply significant percentages, if not all, of our national requirements for those commodities. Columbium, titanium, and aluminum mineral resources fall into this category. Their development however, is dependent on one or more of several economic factors including availability of relatively cheap imports, technologic breakthrough in improved beneficiation and recovery, government subsidy, availability of large amounts of venture capital, and, in the case of aluminum from dawsonite, on large-scale development of oil shale in areas containing the saline minerals.

Other commodities, some of which have had historic production, have the potential of supplying lower but still significant percentages of our strategic mineral requirements. These include tungsten, tin, thorium, fluorspar. These commodities have been or are being produced and could supply significant percentages of our national needs during periods of international crises. Future production of tungsten and fluorspar is more dependent on favorable price structure than any other factor. Tin, produced as a by-product of molybdenum, is dependent on production at Climax. Thorium demand is relatively low now, but greater reliance on nuclear power generation and conversion to high-temperature gas reactors could greatly increase the demand for thorium.

Current research conducted by the Department of Interior Bureau of Mines Salt Lake City Research Center points to a technologic breakthrough in recovery of titanium, from perovskite. Preliminary results of research indicate almost a twofold increase in the extraction of titanium from perovskite concentrate. Previous methods recovered only about 50 percent of the titanium; however, the new process recovers more than 95 percent. This new improved process of recovering titanium from concentrate is an example of technologic breakthroughs needed to allow economic recovery and production of domestic strategic minerals.

Strategic minerals are so important to our high-tech industries, aircraft industry, and to national security, and present imported supplies are so vulnerable that intensive research to explore for new resources, to develop more efficient technology for beneficiation and recovery of large low-grade deposits should have high priority.

OVERVIEW OF STRATEGIC AND CRITICAL MINERALS IN COLORADO

Strategic minerals are those commodities essential to national defense for which the supply during war is wholly or in part dependent upon sources outside the national boundaries of the United States and for which strict measures controlling conservation and distribution are necessary. Critical minerals, on the other hand, although essential to the national defense, are less difficult to procure during wartime because they can either be domestically produced or obtained in adequate quantities from reliable foreign sources and for which some conservation measures may be necessary for nondefense uses. Usually a chronic domestic shortage exists for strategic minerals; potentially economic reserves may or may not exist. Potentially economic reserves of critical minerals may be relatively abundant, but we may rely heavily on foreign sources of raw ore simply because of economic, social, environmental, or political reasons. The lists for strategic and/or critical minerals have changed with time. Since the first list in 1941, a number of new minerals have in recent years been added to the list. These include minerals such as cobalt, niobium (columbium), cesium, and various rare earth elements, in addition to aluminum, antimony, chromium, manganese, optical mica, platinum, nickel, mercury, tin, and tungsten.

In 1975, 29 critical minerals were listed, 17 of which were designated strategic. They include optical mica, columbium, cesium, manganese, tantalum, cobalt, bauxite, the platinum group metals, asbestos, chromium, tin, fluorine, nickel, mercury, tungsten, antimony, and selenium. Of these, supply problems are greatest for chromium, platinum, and cobalt. Readily available supplies are limited, primarily from Zaire, Zambia, Zimbabwe (Rhodesia), and South Africa. International problems jeopardize these supplies.

The Strategic and Critical Material Stockpiling Act authorizes the stockpiling of these commodities and is designed to decrease, and preclude when possible, a dangerous and costly dependence by the U.S. upon foreign sources for supplies of these materials in times of national emergency. Such a stockpile supply should be sufficient to sustain the U.S. for a period of not less than three years in the event of a national emergency.

The key elements of the current stockpile policy are that: 1) the stockpile should be sufficient to meet the military, industrial, and essential civilian needs for the first three years of a war; 2) the war scenario shall be consistent with the scenarios being developed by the Emergency Mobilization Preparedness Board chartered by Executive Memorandum dated December 17, 1981; and 3) goals reflect detailed assumptions regarding changes in a wartime civil economy, wartime foreign trade pattern, shipping losses, wartime political and economic stability of foreign nations, and alternate foreign and domestic production levels for stockpile materials.

The U.S. has a wide variety of mineral resources that fall within the strategic and critical definition. There is, for example, significant production of aluminum metal (even though we are 95 percent dependent on foreign bauxite ore), beryllium, copper, iodine, mercury, molybdenum, titanium, and lead. We also have potential significant but undeveloped resources of nonbauxitic aluminum ore, cobalt, platinum, nickel, and titanium-bearing materials. For a variety of reasons, principally economic, that are in part caused by foreign government subsidization of their productive capacity and foreign relationships, our domestic industry has not found it profitable to invest in domestic production of many of these strategic and critical minerals.

Thus far, the U.S. has relied on the strategic stockpile as the primary means of providing for national defense objectives. Analyses are being made, however, to determine whether utilization of defense production act incentives might be more cost effective than stockpile purchases.

The primary purpose of this report is to attempt to answer the question, "How does Colorado fit into this overall production scheme of strategic and critical minerals?" Historically, Colorado is most famous for its gold, silver, and base-metal mining. In addition the State has been a significant source of molybdenum, uranium, radium, vanadium, tin, tungsten, and fluorspar. As will be seen in the following sections, Colorado holds important reserves of many of these commodities and others, namely titanium, thorium, columbium, and aluminum, some of which occur as unconventional ores.

Colorado could, under favorable economic and political climates, help reduce our import dependence on several of these strategic minerals.

The limiting factors to development of Colorado's strategic resources include uncertainty in oil shale economics and technology, adverse terrain and climate, inaccessibility and absence of rail lines in some areas; shortage of water, lack of adequate in-state smelting/refining capacity and regional industrial infrastructure; potential metallurgical difficulties with complex or unconventional ores; land-use and environmental conflicts; and possibly discouraging permitting and taxation aspects.

ACKNOWLEDGMENTS

This report was funded and made possible by the U.S. Bureau of Land Management through the U.S. Geological Survey contract 14-08-001-A154 dated 7/8/83 and modified 9/9/83. We wish to thank John Matis of the Bureau of Land Management and Charles Thorman of the U.S. Geological Survey for their assistance, and critical review of the manuscript. The Climax Molybdenum Company (a division of AMAX) kindly permitted us to publish its 1982 production figures for molybdenum, tin, and tungsten. We also thank David Banks for typing the manuscript and Cheryl Brchan of the Colorado Geological Survey for assistance in the preparation of the minerals occurrence map.

COLORADO METALS POSITION

To set the proper perspective for discussions of strategic metals potential, we should briefly look at past and present metal production in the State. Colorado has achieved national prominence in the last 120 years from the discovery and development of gold, silver, and base metals at such historic camps as Central City, Leadville, Aspen, Cripple Creek, and Silverton. Although now nothing like the boom days of the late 1800's, most of these districts and others in the productive Colorado Mineral Belt still yield metals. However, their levels of activity and the frequency of periods of renewed interest are tied closely to metal prices, which can fluctuate dramatically in response to national and international economic forces.

Perhaps less well known than the precious and base metals are several other metals groups in which Colorado also has achieved prominence. Their emergence resulted from early-day scientific discoveries (radium), expanded or new industrial applications (vanadium, molybdenum, tungsten, and uranium), by-product or coproduct recovery from other operations (tin, tungsten, columbium, tantalum), and needs for wartime domestic sources (manganese, lithium, uranium, tungsten). Still others were recovered either as primary or accessory products from one or only a very few sites (mercury, bismuth, rare earths, nickel) or as small-scale intermittently produced commodities from scattered sites (manganese, iron, beryllium).

As important as the discovery and early exploitation of these metallic deposits was the need to mill, concentrate, smelt or refine the ores into useful metals. Some Colorado ore deposits might have remained in the earth had it not been for the foresight and courage of some to establish accessible local and regional facilities to treat the ores. Most of the numerous small mills, concentrators, and amalgamators were located either at the larger mine sites or in nearby mining camps and towns. Smelters generally were constructed and operated in the larger regional mining and population centers served by the railroads--Colorado Springs, Pueblo, Canon City, Salida, Leadville, Gunnison, Durango, and Denver.

The Colorado metals position can be conveniently summarized in tabular form. Table 1 lists 57 industrially useful metals and the nine stockpile-designated nonmetals and compares Colorado's occurrences, past, present, and future production potential, current processing capabilities, mineralogy, mode of recovery, and stockpile designations and status. Of all the metals listed, 50 (88 percent) have been found in Colorado. Certainly not all occurrences are considered potentially economic. As noted above, a number of metals occur in only one or at most several localities as mineralogical curiosities or as minor accessory minerals. Some metals (gallium, germanium, scandium, some rare earths) have not even been directly observed but only identified analytically as trace elements in coal and other minerals.

Of the 50 occurring metals, 28 have been economically produced in Colorado to some degree. The famous mining camps noted earlier and others yielded the bulk of the State's gold, silver, and base metals. Most of the districts lie in the Colorado Mineral Belt, a prominent structural zone extending from Boulder County southwest into Gunnison County. Some researchers extend it farther to include the San Juan Mountains in southwestern Colorado. The emphasis of this report will, however, be on those areas containing most of the less common strategic metals.

TABLE 1. Summary of Colorado's minerals position in relation to national strategic stockpiles.

Metallic Element or Nonmetal	Chemical Symbol	Colorado Occurrence	Type of Ore or Occurrence in Colorado*	Past Production	Present Production	Production Value Rank in Colorado, 1980	Mode of Recovery[1]	Future Production Potential	In-State Ml/Sm Capacity	Stockpile Status[3]	Form of Current Stockpile Inventory or Requirement (in decreasing order of quantities) [3]	% Consumption from Imports[4]
PRECIOUS METALS:												
Gold	Au	x	E1-T-E2-A	x	x	4	1-2	x	x			21
Silver	Ag	x	S1-S2-E1-E2-T-Cl-Br-I-A	x	x	2	1-2	x	x	+	metal	61
Platinum Group:									(5)	–	metal	84
Iridium	Ir	x[6]	BS							–	metal	
Osmium	Os	x[6]	BS									
Palladium	Pd	x	E2							–	metal	
Platinum	Pt	x	BS-E2							–	metal	
Rhodium	Rh											
Ruthenium	Ru											
BASE METALS:												
Copper	Cu	x	S1-S2-S3-C-O-E1	x	x	10	1-2	x	x	–	metal	17
Lead	Pb	x	S1-S2-S3-C-O-Se	x	x	6	1-2	x	x	–	metal	11
Zinc	Zn	x	S1-C-Si-Cx	x	x	7	1-2	x	x	–	metal	66
REFRACTORY METALS:												
Molybdenum	Mo	x	S1-XO	x	x	1	1	x	x			EX
Niobium (or Columbium)	Nb (Cb)	x	O-XO-E2-F	x			1-2	x		(7)	concentrate; carbide; ferro; metal	100
Rhenium	Re											W
Tantalum	Ta	x	XO-F	x			1-2	x		(8)	mineral; metal; carbide	90
Tungsten	W	x	XO	x	x	9	1-3	x	x	(9)	ore+concentrate; carbide; metal; ferro	48
LIGHT METALS:												
Aluminum	Al	x	C-S3-Cx-O					x		(10)	bauxite; metal	96[11]
Beryllium	Be	x	O-Si	x			1-2	x		(12)	ore (oxide); Be-Cu alloy; metal	W
Lithium	Li	x	Cx-P-Si	x			1	x				EX
Magnesium	Mg	x	C									2
RADIOACTIVE METALS:												
Radium	Ra	x	E2	x			2					NA
Thorium	Th	x	P-Si-Cx	x			2	x		+	nitrate	100
Uranium	U	x	XO-O-Cx-P	x	x	3	1-2	x	x			10[13]
FERROUS METALS:												
Chromium	Cr	x	O							(14)	chromite; ferro; metal	77
Iron	Fe	x	O-S1-S2-C	x	x	11	1	x	x[15]			37
Manganese	Mn	x	O-E2-C-Si-S3	x			1	x		(16)	ore; ferro; dioxide; metal	99
Vanadium	V	x	Cx-XO-O	x	x	5	1-2	x	x	–	ferro; pentoxide	52

Metallic Element or Nonmetal	Chemical Symbol	Colorado Occurrence	Type of Ore or Occurrence in Colorado*	Past Production	Present Production	Production Value Rank in Colorado, 1980	Mode of Recovery[1]	Future Production Potential	In-State Ml/Sm Capacity	Stockpile Status[3]	Form of Current Stockpile Inventory or Requirement (in decreasing order of quantities) [3]	% Consumption from Imports[4]
RARE EARTHS[17]:				x[18]	x[18]				([18])	([19])	oxides	18
Cerium	Ce	x	P-Si-F	x			1-2	x				
Lanthanum	La	x	P-Si-F-E2	x			1-2	x				
Lutetium	Lu	x	E2	x								
Neodymium	Nd	x	E2									
Samarium	Sm	x	E2									
Terbium	Tb	x	E2									
Yttrium	Y	x	P-Si-F-C-E2	x			1-2	x				
Ytterbium	Yb	x	E2									
MISCELLANEOUS:												
Antimony	Sb	x	S1-S2-S3	x			2-3			+	metal	52
Arsenic	As	x	S2-S1-E1	x			3					W
Barium	Ba	x	S3	x[20]			1-2					64
Bismuth	Bi	x	S1-E1-E2-O-C-XO	x			2-3			–	metal	W
Cadmium	Cd	x	E2-S1	x		12	2-3		x[21]	–	metal	69
Cesium	Cs	x	E2									100
Cobalt	Co	x	S2							–	metal	96
Gallium	Ga	x	E2									61
Germanium	Ge	x	E2									NA
Hafnium	Hf											W
Indium	In								x[21]			NA
Mercury	Hg	x	S1-T-E1	x			1			+	metal	25
Nickel	Ni	x	S1-S2-Si-T	x			2			–	metal	77
Rubidium	Rb											NA
Scandium	Sc	x	E2									100
Selenium	Se	x	Se									37
Silicon	Si	x	Si					x				30
Strontium	Sr	x	S3-C									100
Tellurium	Te	x	T-E1	x			2-3					W
Thallium	Tl								x[21]			100
Tin	Sn	x	O	x	x	8	3	x	x	+	metal	72
Titanium	Ti	x	O-XO					x		–	sponge metal; rutile	10
Zirconium	Zr	x	Si									W
NONMETALS[22]:												
asbestos		x	Si							+	amosite; chrysotile	65
fluorspar:												
acid		x	F	x			1	x	x	–	ore (>97% CaF_2)	
metallurgical		x	F	x			1	x	x	–	ore (<97% CaF_2)	
graphite		x	E1	x			1			–	crystalline; amorphous; lump	100
indus. diamond		x	E1		x[23]			x	x[23]	+	bort; stones; dies	100
iodine		x	I							+	solid	W
mica (sheet)		x	Si	x			1-2			([24])	splittings; block; film	100
quartz crystal		x	Si	x			1			+	crystal	EX
talc		x	Si							+	block & lump steatite	EX

Footnotes to Table 1

[1] 1=primary ore; 2 = coproduct; 3 = by-product of smelting/milling

[2] status of 11/30/83, from U.S. Bur. Mines Mineral Commodity Summaries, 1984. Symbols: + = excess; – = deficit

[3] from Bullis and others (1981)

[4] Estimated net import reliance as a percentage of apparent consumption as of 1983 (from U.S. Bur. Mines Mineral Commodity Summaries, 1984, except where noted otherwise). Abbreviations: W = withheld; NA = not available; EX = net export. Platinum Group metals and Rare Earths not reported individually. Figure for barium is barite (ground, crude, blanc fixe). Figure for fluorspar is 1982 estimate (1983 withheld). Figure for gallium is 1982 estimate. Figure for graphite is 1981 estimate (1983 withheld). Net export for natural electronic and cultured quartz crystal; figure not available for lasca. Figure for scandium is 1980 estimate. Figure for titanium is rutile (TiO_2); figure for sponge metal withheld for 1983 but estimated at 9% in 1982; figure for ilmenite withheld for 1982 but reported as 12% for 1982.

[5] near-future recovery capacity anticipated for Pt Group metals

[6] reported as iridosmium

[7] deficit for carbide and concentrates; excess for metal and ferro (no goal set). Stockpile also contains nonstockpile-grade concentrates and ferro.

[8] excess for metal and powder (no goal set); deficit for Ta minerals

[9] excess for ore and concentrates; slight deficits for metal and carbide; excess for ferro (no goal set). Stockpile also contains nonstockpile-grade ore and concentrates, metal, ferro, and carbide.

[10] deficit for both metal and bauxite

[11] figure is import reliance for bauxite and alumina; 18% net import reliance for Al metal

[12] at goal for Be ore; deficit for metal and Be-Cu alloy

[13] estimated from 1980 delivery commitments, foreign sales, and imports of U_3O_8 (from U.S. Dept. Energy, Statistical Data of the Uranium Industry, 1/1/81)

[14] excess for ferro; deficit for ore and metal

[15] includes capacity for treating iron ore for steel manufacture and capacity for recovering iron pyrite concentrates; however, present furnace and mill capacity is being converted to fabrication only

[16] excess for electrolytic metal, silico Mn, and medium-carbon Fe for which no goals were set; excess for high-carbon ferro, chemical ore, and natural ore for battery; deficit for synthetic dioxide and metallurgical ore

[17] includes only those rare earths occurring in Colorado

[18] includes past recovery of rare-earth (monazite) concentrates at Climax Mine and present rare-earth recovery (La, Nd, Pr) from non-Colorado ores

[19] total inventory authorized for disposal as no stockpile goals were set

[20] mined and used as barite in nonmetallic form

[21] past thallium recovery was smelter by-product from non-Colorado ores; thallium recovery discontinued in 1981. Cadmium and indium presently recovered as smelter by-products

[22] those listed are the only nonmetals considered for stockpile objectives

[23] diamondiferous kimberlite currently being explored and evaluated

[24] deficit for block; excess for splittings and film

* EXPLANATION FOR COLUMN 4 (listed in table in approximate order of decreasing significance):

A	natural alloy (gold and silver only)
Br	bromide
BS	unspecified black sand occurrence/concentrate
C	carbonate
Cl	chloride
Cx	complex radical
E1	native element
E2	element contained in unknown form in other mineral
F	fluoride
I	iodide
O	oxide
P	phosphate
S1	simple sulfide
S2	bimetal/polymetal sulfide
S3	sulfate
Se	selenide
Si	silicate
T	telluride
XO	metal-oxygen anion

All of the four common light metals occur in Colorado, but only beryllium and lithium have been commercially recovered. The mineral beryl, the prime source of beryllium, has been recovered intermittently from its most common source, pegmatites, in Fremont, Park, Teller, Douglas, Jefferson, Boulder, and Larimer Counties.

Important nonpegmatitic sources or vein deposits yielded beryl and bertrandite in Park, Chaffee, and Teller Counties. In fact, the first vein beryllium deposit mined in the U.S. was found in the Badger Flats district near Lake George (Park County). Gem-quality and specimen beryllium minerals are well known from central Colorado collecting localities. Most of our lithium comes from pegmatites in the Carolina lithium belt, but some is recovered from Nevada brines. During World War II, however, the Quartz Creek district in Gunnison County was an important source of this metal. The pegmatites there yielded lithium mica, lithium tourmaline, and spodumene, along with mica, beryllium, and columbium-tantalum.

Uranium has dominated the production picture in the radioactive metals group. Most of this comes from Jurassic-age sedimentary rocks in the Uravan Mineral Belt of Mesa, Montrose, and San Miguel Counties and southeastern Utah. Other significant production has come from Tertiary-age sedimentary rocks in Moffat, Rio Blanco, and Fremont counties. Vein deposits have been worked in the Marshall Pass area (Gunnison and Saguache Counties) and at what is considered to be North America's largest vein uranium operation, the Schwartzwalder Mine northwest of Denver. Historic production of thorium has been very small because of the metal's extremely limited uses. Small quantities mined in Colorado came from thorite veins in the Wet Mountains of south-central Colorado and in the Powderhorn district (Gunnison County). Thorium also was recovered in rare-earth (monazite) concentrates from the Quartz Creek district (Gunnison County) and from the Climax molybdenum mine (Lake County). As will be seen later, Colorado's thorium deposits hold significant future potential in the generation of atomic energy.

All but one of the ferrous metals group have been mined in Colorado. Manganese, in the form of oxides and hydroxides, occurs in numerous geologic environments not necessarily confined to the Colorado Mineral Belt. Except for mines in the Leadville, Bonanza, and Rosita districts, production has been small. More important reserves occur as silicates and carbonates in the San Juan Mountains. Iron, too, occurs in rocks of diverse geologic origin and age scattered across the mountains and West Slope. Most of the historic production (in the form of magnetite, hematite, and limonite) was consumed as flux in the early smelters, as low-grade iron ore for steel manufacture in Pueblo, and as nonmetallic oxides for pigments, soil conditioners, and heavy aggregate. Currently vanadium is the State's most important ferrous metal, produced as a coproduct in the processing of sedimentary uranium ores on the West Slope.

The rare earths are an unusual group of elements in that they are actually metals and not "earths." Along with yttrium they comprise the Lanthanide Series of elements in the periodic table (atomic numbers 39 and 57 through 71). Although rare-earth demand is small compared to other metals, their varied and growing industrial applications range from nonferrous alloys to glass manufacture. Rare-earth ore mined in Colorado occurred as monazite and other complex silicates, fluorides, and fluorocarbonates in pegmatites of the

Quartz Creek district (Gunnison County) and South Platte district (Jefferson County). Only three principal rare earths--cerium, lanthanum, and yttrium--were recovered. The remaining metals listed in Table 1 were identified in trace-element analyses of coal. Even though future production potential exists in the South Platte district, these metals will not be considered in this report because no stockpile goals have been set, and the existing surplus has been authorized for disposal.

In the refractories metals group Colorado leads the free world in production of molybdenum, a critical strengthening metal in the manufacture of high-temperature steels and an important component in refractories, lubricants, catalysts, industrial chemicals, and electronic and aerospace devices. The Climax and Henderson Mines that produce the primary ore mineral, molybdenite, are classic geologic examples of this type of mineralization. In addition the Climax Mine produces another refractory metal, tungsten, as a by-product and a substantial quantity of tin, enough, in fact, to rank it as the respective second and first leading domestic producers of those two metals. Before by-product tungsten recovery began at Climax in 1948, Boulder county was the State's and nation's principal productive area, and the output of wolframite, scheelite, and ferberite from that district was especially important during the World Wars I and II. Small quantities of two other refractories, columbium (or niobium) and tantalum, have been recovered as coproducts with rare earths and other minerals from pegmatites.

Nineteen of the 23 miscellaneous metals occur in Colorado, but only seven have seen economic recovery. All but tin, mercury, and nickel were recovered chiefly as smelter by-products. Only very small production was recorded for the remainder (except tin). Barium was mined as the sulfate mineral, barite, and consumed for nonmetallic uses rather than as a source of metallic barium.

The nine stockpile-designated nonmetals all occur in Colorado, and minor production was recorded for graphite, sheet mica, and quartz crystal. Until 1973 Colorado was a significant source of fluorspar and at one time contributed over one-fourth of the nation's production value. The principal districts include Jamestown (Boulder County), Northgate (Jackson County), Wagon Wheel Gap (Mineral County), and Browns Canyon (Chaffee County). Following the 1975 discovery of diamonds in the State Line district of southern Wyoming and northern Colorado, diamondiferous kimberlitic diatremes are undergoing formal field exploration, sampling, and pilot-plant testing. Although testing is not yet complete, industrial diamond has been included in Table 1 for potential future production.

Columns 4 and 8 in the table show basic ore mineralogies and modes of recovery. Mineral composition can be a deciding factor in recovery feasibility because some of the more complex or unconventional compositions and mineral structures can cause metallurgical and economic difficulties in smelting.

Column 10 identifies those metals and nonmetals for which Colorado currently has some type of recovery capacity--milling, concentrating, smelting. For some metals, namely rare earths, cadmium, indium, and thallium in-state plants recover metals from ores and concentrates produced outside Colorado. Current capacity includes precious and base metals, molybdenum with by-product tin, tungsten and pyrite, uranium, vanadium, rare earths, iron, fluorspar (inactive), and diamond (pilot plant). Molycorp's plant at Louviers (Douglas

County) recovers several rare-earth oxides from mill concentrates of ore mined at Mountain Pass, California. ASARCO's Globe plant in Denver, Colorado's only smelter, recovers gold, silver, copper, lead (litharge), cadmium, indium, bismuth, and several nonmetallic substances from concentrates, milled ore, some crude ore, dross, and smelter flue dust. Thallium recovery was discontinued because of the liability risk associated with thallium toxicity. Molybdenum concentrates are recovered at two AMAX plants--one at the Climax Mine on Fremont Pass and one in Summit County across the Continental Divide from the Henderson Mine (Clear Creek County). By-product molybdenum also is recovered from uranium ore processed at Cotter Corporation's mill in Canon City (Fremont County). Other uranium-vanadium mills and ore sampling/buying stations are located at Rifle (Garfield County), Whitewater (Mesa County), Maybell (Moffat County), and at Uravan and Naturita (Montrose County). Iron ore was processed and used in the manufacture of steel at CF&I Steel Corporation's mill in Pueblo. Due to the recent severe troubles in the world steel industry, the Pueblo plant, as of the end of 1983, converted to fabrication.

Columns 11, 12, and 13 in Table 1 summarize 1983 stockpile status and import reliance for designated strategic minerals. Excess stockpiles are reported for silver, thorium, rare earths, antimony, mercury, tin, asbestos, diamond (industrial), iodine, quartz crystal and talc. Deficits are indicated for platinum-group metals, copper, lead, zinc, vanadium, alumina, bismuth, cadmium, cobalt, nickel, titanium, fluorspar, and graphite. The remaining commodities are stockpiled in several forms including ores, concentrates, metals, and other compounds and may have deficits for some and excesses for others--columbium, tungsten, beryllium, chromium, manganese, and mica.

Finally to emphasize the importance of Colorado's mineral production compared to national totals, the U.S. Bureau of Mines in 1981 ranked Colorado first in output of molybdenum, vanadium and carbon dioxide, second in tin and tungsten (by-products of molybdenum milling), third in lead, fourth in silver, seventh in gold and zinc. Impressive.

Next we will examine the geology, mineralogy, uses, and potential of those strategic metals and nonmetals for which we believe Colorado holds the greatest potential for future production (exclusive of precious and base metals)--tungsten, tin, thorium, columbium, titanium, manganese, aluminum, vanadium, fluorspar. Future production of any of these commodities in Colorado may not necessarily depend on a national emergency, and all or a portion of any production would not necessarily be added to federal stockpiles.

COMMODITY SUMMARIES

Tungsten

Tungsten, a silvery gray, hard, brittle, nonmagnetic metal, has several properties that make it unique and valuable. It has the highest melting point (3,410°C) of all metals; its extremely low vapor pressure makes it useful for electric wiring in furnaces, targets for X-ray tubes, contacts, arcing points; its higher electrical efficiency is responsible for its almost exclusive use in light filaments. The first significant use of tungsten was for high-speed tungsten-manganese steel developed around the middle of the nineteenth century. Principal uses today are: (1) tungsten carbide in cutting and wear-resistant materials, welding and hard-facing rods (63 percent of consumption); (2) as an alloy for high-speed and tool-and-die steels, superalloys, and nonferrous alloys (16 percent); (3) mill products from essentially pure metal (16 percent); and (4) various chemicals and compounds for nonmetallurgical applications (5 percent).

The most common tungsten ores occur as a compositional series of manganese and iron tungstates whose end members are huebnerite ($MnWO_4$) and ferberite ($FeWO_4$) and intermediate-composition wolframite. Other associated tungsten ores include the calcium tungstate, scheelite ($CaWO_4$), in which molybdenum may partially substitute for tungsten to give powellite, $Ca(Mo,W)O_4$.

Tungsten is one of the rarer elements in the earth's crust, with an average abundance estimated at 1 to 1.3 ppm. Granites contain the highest concentrations, but because the residual fluids of crystallizing magmas concentrate tungsten, it often precipitates as wolframite or scheelite in wallrock contact zones in metamorphic rocks. It follows that deposition also occurs in hydrothermal veins, stockworks and related deposits where it is often associated with molybdenum, such as in the porphyry molybdenum deposit at the Climax Mine (Lake County) where huebnerite and wolframite are recovered as by-products. Contact metamorphic deposits (tactites) in California, Nevada and Montana are the main domestic source of tungsten where it occurs as scheelite. More than 60 percent of the world's reserves, however, occur as tungsten-bearing quartz veins associated with granitic intrusive rocks.

Colorado's tungsten industry dates from 1899 when the first ores were produced in the State's most prominent tungsten district--Boulder County. Also in 1899 or in the following year, concentrates were first shipped from the Cement Creek area of San Juan County near Silverton. The third producing area, the Climax molybdenum mine, began shipping by-product tungsten in 1948. Elsewhere in Colorado minor tungsten production has been recorded from (1) Stove Prairie area, north-central Larimer County, (2) Masonville district, southeast-central Larimer County, (3) Monte Cristo Gulch area, southern Summit County, (4) Alma district, northwestern Park County, (5) Tarryall Springs area, eastern Park County, (6) Eightmile Creek area, northeastern Fremont County, (7) Copper Creek area, south-central Fremont County, (8) Cleora district, southeastern Chaffee County, (9) Tincup district, eastern Gunnison County, and (10) Wolf Creek area, southern Gunnison County (Hobbs, 1968).

A Boulder County gold miner named Towner is believed to have discovered tungsten ore in the 1860s near the site of the Old Coanger shaft but discarded it as "worthless black iron". Another miner, John H. Knight, recognized the wolframite in the early 1890s, and his display of specimens at the Paris Universal exposition in 1899 caused much excitement. Mr. Beddig was probably the first to produce tungsten ores from the district that same year. In 1900 S. T. Conger and W. H. Wannamaker began production from the district that would shortly become the country's leading source of tungsten and remain so for many years. The mines produced tungsten concentrates nearly continuously from 1900 through 1958. Even early in the district's history, eastern steel interests recognized the production potential, and activities were dominated by several large companies: Wolf Tongue Mining Company (subsidiary of Firth-Sterling Co.), Primos Mines Company (subsidiary of Primos Chemical Co.), Vasco Company (subsidiary of Vanadium Alloy Steel Co.), and later the Vanadium Corporation of America.

The material demands brought on by World War I caused dramatic price increases that led to a peak output of 2,707 short tons of equivalent 60-percent-WO_3 ore in 1917, or 1,624.2 short tons of WO_3, equivalent to 162,420 units (the common quantity of measurement for tungsten is the "unit," equal to 20 lb). Following the war, prices dropped drastically, forcing the district to close down entirely in 1921 and 1922. Production resumed in 1923 but at no more than half the levels of the 1910s. Output again increased during World War II in response to higher prices but overall was small compared to that from low-grade scheelite from Idaho, Nevada, and California. Greatly increased production from 1951 through 1956 resulted from Defense Minerals Exploration Administration (DMEA) programs. The district has produced only small amounts of tungsten since the late 1960s. Cumulative production from the district through 1956 amounts to 1,514,484 units of WO_3, or about 24,800 short tons of equivalent 60-percent-WO_3 concentrated ore (Table 2).

The Boulder tungsten district extends from Arkansas Mountain about 4 miles west of Boulder 10 miles west-southwest to Nederland. The belt is one to two miles wide flaring to about 3 miles at the southwestern end near Nederland (Tweto, 1947).

The district lies on the northwest side of the Precambrian Boulder Creek batholith, a granitic pluton intruded across the northwest-trending metamorphic foliation of the Idaho Springs Formation in the central Front Range. Precambrian gneissic aplite dikes and pegmatites cut the granite. A few mafic dikes extend into the western part of the district from the Tertiary (Laramide) stocks at Caribou and Eldora several miles west of Nederland.

The structure of the district is characterized by four prominent Laramide fault zones or "breccia reefs" that cut both the granite and metamorphics at 2- to 3-mile intervals and include (from northeast to southwest) the Hoosier, Livingston, Rogers, and Hurricane Hill reefs. The Hoosier and a fifth reef, the Maxwell, to the northeast strongly influenced the deposition of telluride ores in the noted Gold Hill district to the northeast. The Rogers reef was an important control on uranium mineralization in the Ralston Creek area in Jefferson County to the southeast. Similarly in the tungsten district, the mineralized fissures and cross-fractures lie very near the reefs in a conspicuous 2-mile-wide zone trending generally N70°E and lying in the granitics between the Hoosier and Hurricane Hill reefs. However, some of the district's most productive mines, one mile northwest of Nederland, developed veins associated with a satellitic granite pluton and concordant pegmatites and granitic stringers in the metamorphics. At Tungsten Mountain, two mile southeast of Nederland, a second cluster of northeast- and

Table 2. Tungsten production in the Boulder County district (compiled from Belser, 1960; U.S. Geological Survey Mineral Resources of the U.S.; U.S. Bureau of Mines Mineral Yearbooks). Concentrate figures reported at given grades have been recalculated to equivalent 60 % WO_3 (standard reporting unit). Some discrepancies may exist between reported units WO_3 (from Belser, 1960) and concentrates due to uncertainty of inclusion of minor production from other counties. Units WO_3 and lb W for 1956 were estimated by converting reported state total concentrates (at 60 % WO_3) to lb W and subtracting reported Climax production. Equivalent tonnages for many years were calculated from reported units WO_3. One unit WO_3 = 20 lb WO_3. X = small unknown production.

Year	Concentrated Ore (short tons)	Grade (% WO_3)	Equivalent Tonnage at 60 % WO_3	Units WO_3	lb W
1899	X	-	-	-	-
1900	40	63	46	2,760	44,160
1901	-	-	70	4,200	67,200
1902	-	-	192	11,540	184,640
1903	-	-	230	13,800	220,800
1904	-	-	380	22,800	364,800
1905	-	-	607	36,400	582,400
1906	565	-	725	43,500	696,000
1907	-	-	1,146	68,760	1,100,160
1908	-	-	584	35,040	560,640
1909	-	-	993	59,580	953,280
1910	-	-	1,221	73,260	1,172,160
1911	-	-	730	43,800	700,800
1912	-	-	775	48,720	779,520
1913	-	-	953	57,180	914,880
1914	-	-	467	28,020	448,320
1915	-	-	963	57,780	924,480
1916	-	-	2,401	144,060	2,304,960
1917	-	-	2,707	162,420	2,598,720
1918	-	-	1,791	114,600	1,833,600
1919	-	-	147	7,800	124,800
1920	-	-	25	12,960	207,360
1921	0	-	0	0	0
1922	0	-	0	0	0
1923	-	-	241	14,460	231,360
1924	-	-	123	1,500	24,000
1925	-	-	201	12,060	192,960
1926	-	-	232	13,920	222,720
1927	-	-	332	19,920	318,720
1928	-	-	229	13,740	219,840
1929	-	-	152	9,120	145,920
1930	-	-	47	2,820	45,120
1931	-	-	98	5,880	94,080
1932	X	-	-	X	X
1933	-	-	86	5,160	82,560
1934	-	-	342	20,520	328,320
1935	519	45	390	31,140	498,240

Table 2. (continued)

Year	Concentrated Ore (short tons)	Grade (% WO_3)	Equivalent Tonnage at 60 % WO_3	Units WO_3	lb W
1936	256	42.45	180	10,816	173,056
1937	303	43.38	219	13,144	210,304
1938	360	40.05	240	14,418	230,688
1939	617	46.59	479	28,746	459,936
1940	810	-	657	43,559	696,944
1941	810	-	646	38,740	619,840
1942	492	46	377	22,810	364,960
1943	412	50	342	20,522	328,352
1944	-	-	299	17,955	287,280
1945	-	-	252	15,136	242,176
1946	-	-	208	12,473	199,568
1947	-	-	61	3,678	58,848
1948	-	-	31	1,839	29,424
1949	-	-	2	96	1,536
1950	-	-	9	539	8,624
1951	-	-	54	3,258	52,128
1952	-	-	111	6,683	106,928
1953	-	-	319	19,143	306,288
1954	-	-	263	15,797	252,752
1955	-	-	265	15,935	254,960
1956	-	-	166	9,987	159,792
1957	X	-	-	X	X
1958	X	-	-	X	X
1959	0	-	-	0	0
1960	0	-	-	0	0
1961	0	-	-	0	0
1962	0	-	-	0	0
1963	0	-	-	0	0
1964	0	-	-	0	0
1965	0	-	-	0	0
1966	X	-	-	X	X
1967	X	-	-	X	X
1968	X	-	-	X	X
1969	X	-	-	X	X
1970	0	-	-	0	0
1971	0	-	-	0	0
1972	0	-	-	0	0
1973	0	-	-	0	0
1974	X	-	-	X	X
1975	0	-	-	0	0
1976	X	-	-	X	X
1977	X	-	-	X	X
1978	X	-	-	X	X
1979	0	-	-	0	0
1980	0	-	-	0	0
1981	0	-	-	0	0
1982	0	-	-	0	0
TOTALS (1900-1956)			24,806	1,514,494	24,231,904

east-northeast-trending veins lie next to the short northwest-trending Main-Cross reef and cut across the northwest trends of the metamorphics and concordant pegmatites, granitic gneiss and aplite stringers. The district's more productive veins appear to have been the relatively short, north- and northeast-trending veins in the western part of the district, contrasting with the longer, lower grade, northeast- and east-northeast-trending veins in the central and eastern areas.

Small high-grade ore shoots occur as fissure fillings in the veins with ferberite as the principal ore locally grading into low-manganese wolframite and accessory scheelite. Most of the irregular, elliptical or chimneylike shoots dip steeply to the north in the north- and northeast-trending veins, but those in the east-northeast-trending veins plunge decidedly more to the east. As it's known in the district, "soft ore" is friable, coarsely crystalline ferberite filling brecciated country and vein quartz. Fine-grained ferberite disseminated through fine-grained quartz is the "horn ore" and is most common in the eastern part of the district. Soft ore is more amenable to gravity concentrating than the horn ore, which requires fine grinding and usually produces excessive slimes. Associated with the ferberite quartz veins are pre-ferberite sulfides of iron, copper, silver, lead, and zinc and in the central and northeastern part of the district some gold telluride. Gangue minerals include microgranular quartz, sericite, various clay minerals (from argillic alteration), some barite, carbonates, hematite, and magnetite.

Structure, mineral associations, and texture indicate deposition under relatively light load at moderate temperature by hypogene solutions. The deposits are classed as epithermal veins formed near the Laramide magmatic source. Detailed descriptions of the veins, ores, mines and milling methods can be found in Lovering and Goddard (1950), Lovering and Tweto (1953), Belser (1955, 1960), Vanderburg (1932, 1933), and Zadra (1959).

The grade of most of the ferberite ores ran 2 to 20 percent WO_3, with a cutoff of 1.5 to 2 percent. During World War II the high prices for WO_3 enabled ore to be mined at grades as low as 0.8 percent. An unusual aspect of the district's ores is that virtually no progressive grade changes were noted with depth. Ore shoots of comparable grades were found both in the upper and in the deeper parts of the same vein. Because ferberite is less soluble than the country rocks, no substantial enrichment has taken place. Some residual enrichment accounted for the surface or "float" ore worked in the early days. In fact, this type of ore even was placered with a dry-land dredge.

Nonetheless, the apparent grade uniformity bears directly on the question of emplacement and ultimate production potential. Lovering (1941) theorized that tungsten-bearing acidic gaseous solutions were ejected rapidly, perhaps even explosively, from the magma chamber. Reactions with the alkaline wallrocks lowered the acidity of the condensing solutions and induced the precipitation of ferberite through a relatively small vertical interval. However, Tweto (1947) noted that the vein paragenesis also could result from gradual changes in the character of the solutions themselves, that is, a change in the source rather than wallrock reactions, enabling a greater vertical range of ore deposition.

As most ore shoots were only developed from their surface exposures downward to their termini, the known vertical mineralization range of 700 ft closely corresponds to the area's topography. Most of the mines probably did not extend more than an average 100 ft in depth, and the average depth of the thirty most productive mines was only about 340 ft. The larger, deeper mines (approximately 1000 ft) followed some blind ore shoots that happened to lie below or overlap the exposed shoots.

Thus, although essentially all of the outcropping ore shoots have been found, many undiscovered shoots may lie below the historic workings but within easy access. The randomness of their distribution even within the same vein has, however, hampered exploration. About the only satisfactory exploration method was actual mining. Geophysical methods have been useful in locating veins but not ore. Random diamond drilling can easily miss the chimneylike irregular shoots.

The geology and history of development suggest that significant tungsten reserves yet lie within the district. Current information on reserves is lacking unfortunately, but Belser (1955) tabulated estimates for indicated and inferred ore as of 1953 for 109 of the district's several hundred mines (Table 3). Ore categories include dumps and float because of past successful scavenger operations. The reserve estimate (modified to account for production in 1956) excludes what is considered to be negligible production after 1956. Estimated total indicated and inferred reserves are 317,023 units WO_3. Even with substantial reserves at acceptable grade and favorable prices, any major activity in the district appears seriously hampered by the area's increasing attraction for residential and recreational development.

The Climax Mine in central Colorado is located on the west flank of the Tenmile Range where Permian and Pennsylvanian sedimentary rocks have been complexly faulted against Precambrian igneous and metamorphic rocks. The deposit is classified as a molybdenum stockwork in an intensely altered composite porphyry intrusion and contains accessory tungsten, tin, and rare earths.

The Climax ore body began to form in early Tertiary time when the Elk Mountain and Lincoln porphyries were intruded as dikes and sills into the metamorphics. Later, about 30 million years ago, three granitic stocks intruded the porphyries and other country rocks. Two of these stocks, separated by some time interval, caused fracturing above and on the flanks of the stocks where hydrothermal solutions rich in molybdenum, quartz, and tungsten moved through channelways in the stocks and deposited molybdenite, quartz, and tungsten in the fracture zones. The first of these stocks created the Ceresco moly ore body, much of which was later removed by erosion. The third intrusion, the Aplitic Phase of the Climax Porphyry, formed the Lower Ore Body and the Lower Ore Body high-silica zone. The second intrusion is barren.

Postore events included the emplacement of the Porphyritic Granite Stock, two large and many smaller dikes that cut all the older rocks and represent dilution of ore. Their locations are important in mining and ore production. Later intense faulting and fracturing caused major movement along the Mosquito, South and East Faults. Movement on the Mosquito Fault, a major structural feature in central Colorado, dropped the west block downward 8,500 to 9,000 ft relative to the east block. This caused the ore to be cut off in the west block and raised the ore body in the east block where erosion and glaciation removed all but the lower root portion of the Ceresco Ore Body and the upper portion of the Lower Ore Body.

Table 3. Tungsten reserves in Colorado (modified from Belser, 1955, 1956a, 1956b). For Boulder district, figure in parentheses represents Belser's estimate as of 1953 modified to reflect estimated production in 1954-1956. Only totals for indicated and inferred horn ore in Boulder district were given to avoid releasing confidential information. Estimates for San Juan region and other areas are presumed to be totals of indicated and inferred reserves. One unit = 20 lb WO_3.

	Short Tons	Grade % WO_3	Units WO_3
BOULDER DISTRICT (109 mines)			
Soft Ore:			
Indicated ore in place	8,598	3.358	28,874
Inferred ore in place	53,346	2.153	114,953
Inferred ore in stope fills	63,725	0.502	32,000
Inferred ore in dumps	67,600	0.206	13,940
Inferred ore in float	299,166	0.068	20,250
Total Soft Ore	492,435	0.426	210,017
Horn Ore:			
Indicated ore in place	--	2.973	--
Inferred ore in place	--	0.715	--
Inferred ore in stope fills	--	0.500	--
Inferred ore in dumps	--	0.285	--
Inferred ore in tailings	--	0.500	--
Total Horn Ore	207,318	0.717	148,725
Total Soft and Horn Ore	699,753	0.513	358,742 (317,023)
SAN JUAN REGION (13 properties)			
Indicated and Inferred Ore in place	50,550	1.6	84,525
Indicated and Inferred Ore in stope fills	4,500	0.6	2,900
Indicated and Inferred Ore in dumps	16,950	0.5	10,160
Total Indicated/Inferred Ore	72,000	1.3	97,585
CENTRAL/NORTHERN COLORADO (20 properties)			
Indicated and Inferred Ore in place	44,719	0.80	35,992
Total Indicated/Inferred Ore	45,919	0.81	37,192
TOTAL RESERVES (exclusive of Climax)	817,672	--	451,800

Huebnerite and less abundant wolframite postdate the molybdenum mineralization but lie in two zones similar in shape to the ring- or umbrella-shaped moly ore bodies (Wallace and others, 1960). The inner tungsten zone lies primarily between the upper and lower ore bodies but is superposed on both where they merge to the east. The outer zone follows the northwestern part of the upper ore body but diverges from it southward. Some scattered high-grade tungsten has been found peripheral to the eastern and southeastern hanging walls of the upper ore body. Two categories of tungsten mineralization have been recognized at the mine. Fine-grained huebnerite in and adjacent to quartz-pyrite and quartz-topaz-pyrite veinlets occurs in the outer zone and in the lower and outer parts of the inner zone. Coarse-grained huebnerite lies within the inner zone in the high-silica rock between the two ore bodies.

Average annual production from the Climax Mine before the big drop in molybdenum prices and closure of the mine in 1983 was about 54,000,000 lb molybdenum, 2,500,000 lb WO_3, 200,000 lb tin, and 10,000 short tons of pyrite concentrates. No estimates of tungsten reserves at Climax were found. The production record for Climax since the late 1960s (Table 4) shows a fairly constant ratio of tungsten production relative to molybdenum. Assuming this ratio remains constant, one might expect continued by-product tungsten production for the rest of the mine's life, perhaps another 20 to 30 years. Based on production levels of the 1970s, reserves conceivably could total about 50,000,000 lb of WO_3, equivalent to 40,000,000 lb of tungsten. However, the mine very likely will not attain its former production levels due to the apparent restructuring of the molybdenum industry following the last recession.

The third area of significant tungsten production includes the Uncompahgre District (Ouray County), Eureka District (San Juan County), and Ophir or Iron Springs District (San Miguel County) in the San Juan Mountains of southwestern Colorado. Huebnerite mineralization is commonly associated with gold, silver, and base-metal sulfides in veins related to the formation and collapse of the Oligocene San Juan caldera and its nested Silverton caldera.

The first occurrence of huebnerite in the U.S. was described from the Dunmore vein in the 1880s by Hillebrand (1884, 1885). Other descriptions followed in the 1890s. Although most of the mines were worked for precious and base metals, production of tungsten had begun by or 1899. Small intermittent production followed from 1900-1908, during World Wars I and II, and as late as 1969 and 1977. Estimated cumulative production from 1900 through 1953 for at least 24 mines amounted to 350,346 lb WO_3 (17,517 units WO_3). Indicated and inferred reserves are estimated at 72,000 short tons of ore at an average grade of 1.36 percent WO_3, equivalent to 97,585 units WO_3 (Table 4).

Just beyond the northwest rim of the San Juan caldera along Red Mountain Creek (Uncompahgre district), the Dunmore vein cuts quartzites and slates of the Uncompahgre Formation (Precambrian) and unconformably overlying precaldera intermediate-composition flows and breccias of the San Juan Formation (Oligocene). This complex lode, consisting of several base-metal-sulfide veins, is characterized by two breccia pipes--one containing a presulfide hematite chimney and copper ore shoot and another containing a postsulfide tungsten chimney. The tungsten chimney shows several stages of brecciation and mineralization in which huebnerite occurs as scattered blades or clusters with pyrite and sphalerite in coarsely crystalline quartz, often found as stalactitic pendants in large open spaces (Kelley and Silver, 1946).

Table 4. Tungsten and tin production at the Climax Mine, Lake County, Colorado. Figures are short tons molybdenum ore, pounds tungsten concentrates, and pounds tin concentrates. Figures compiled from Colorado Division of Mines annual operator reports and Climax Molybdenum Co. NA = not available; e = estimated

Year	Mo Ore	WO_3	Sn Conc.
1948	2,256,268	NA	NA
1949	2,025,440	NA	NA
1950	2,257,723	NA	NA
1951	4,566,548	NA	NA
1952	4,453,328	NA	NA
1953	6,604,857	520,478	14,785
1954	8,709,000	797,323	12,345
1955	9,227,700	1,058,418	29,652
1956	9,929,552	847,852	19,381
1957	10,551,893	939,104	33,329
1958	6,363,620	549,417	17,421
1959	9,091,544	1,121,952	42,524
1960	11,684,278	1,230,064	34,773
1961	12,274,416	1,807,184	83,962
1962	8,185,012	1,106,466	53,346
1963	12,781,855	1,299,324	56,990
1964	13,711,330	1,449,254	85,531
1965	14,350,982	1,527,000e	91,850e
1966	15,197,824	1,623,085	98,804
1967	15,380,541	1,760,490	78,995
1968	14,617,842	2,030,976	75,572
1969	NA	2,368,930	118,117
1970	NA	2,805,948	179,226
1971	NA	2,310,644	176,495
1972	NA	2,569,545	203,628
1973	NA	2,520,462	215,917
1974	NA	2,487,723	200,548
1975	NA	2,404,392	202,599
1976	NA	2,331,293	159,442
1977	16,689,552	2,252,852	171,466
1978	16,484,007	2,305,289	157,344
1979	NA	2,212,108	156,042
1980	NA	2,326,848	182,518
1981	16,726,173	2,668,616	181,549
1982	6,080,475	969,689	78,255
Total (1953-1982) =		52,202,726	3,181,110

The Dunmore Mine was first worked for gold, silver, and copper, but produced some tungsten ore intermittently from 1937 through 1953.

The most productive tungsten mines in the region are clustered in the upper Cement Creek area (Eureka District) around Gladstone three to six miles north of Silverton. Variably trending veins cut rhyodacitic flows, flow-breccias, and tuffs of the Burns Formation, a widespread unit representing infilling of the collapsed San Juan caldera. A second cluster of mines is situated on the east flank of Sultan Mountain just southwest of Silverton. The host rock is a quartz monzonite stock intruded along the southwest rim of the San Juan caldera.

The third area of production centers on the Ophir district in eastern San Miguel County six to seven miles beyond the west rim of the San Juan caldera. Sedimentary rocks of Permian through Cretaceous age are unconformably overlain by Eocene sedimentary rocks and the early intermediate (precaldera) volcanics. Ophir is located at the east end of the San Miguel Mountains, a series of granodiorite stocks and laccoliths. The Silver Bell Mine at Ophir Loop at the north base of Yellow Mountain originally produced base and precious metals from two northeast-trending veins cutting the stock. Narrow quartz veins on the footwalls contain wolframite and minor scheelite. The Ida vein averages 1.69 percent WO_3 over a 25-ft width.

Although domestic production of tungsten rose to a record level of 7,948,000lb in 1981, the overall trend has been a decrease since 1978, dropping by 1982 to its lowest level (3,354,000 lb) since 1975. Production for 1983 was even lower, about 2,464,000 lb. During the same period, imports of concentrates dropped by more than one-half, and our overall net import reliance (as a percentage of consumption) fell from 58 percent in 1979 to an estimated 39 percent in 1983. Imports for 1979-1982 came principally from Canada, Bolivia, and China.

Since 1980 more than 95 percent of domestic mine production has come from five operations--two each in Nevada and California and from the Climax Mine in Colorado. In 1981 Climax's by-product tungsten accounted for about 27 percent (2,700,000 lb) of the country's output. The production cutback and eventual closure of the mine in 1982 and 1983 reduced its tungsten output to less than one million pounds of WO_3. Even though total U.S. production was drastically less in 1982 (3,354,000 lb tungsten), Climax still accounted for 23 percent. As of 11/30/83, the federal stockpile goals and inventories for tungsten materials were essentially met, with some excess ore and concentrates authorized for disposal (Table 5).

Table 5. National stockpile status for tungsten materials as of 11/30/83 (from U.S. Bureau of Mines, 1983). Figures in pounds. All non-stockpile-grade ore and concentrates have been authorized for disposal.

Material	Goal	Total Inventory	Excess to Goal Authorized for Disposal	Inventory of Non-stockpile-grade Materials
Ore/Concentrate	56,340,000	56,898,000	2,720,000	29,828,000
Metal Powder	1,626,000	1,592,000	--	338,000
Ferrotungsten	--	854,000	--	1,202,000
Carbide Powder	2,032,000	1,950,000	--	114,000

Stafford (1980) estimated the annual domestic demand for primary tungsten by 2000 to range from 43 million to 77 million pounds, with a probable expected demand of 51 million pounds in 2000, or a probable average annual growth rate of 4.5 percent. For the rest of the world growth is expected to reach 3.2 percent, with a cumulative primary demand of 2,170 million pounds. This lower rate can be attributed to the fact that other countries probably will not become as automated as the U.S. So, they will rely more on high-speed steels for cutting and wear-resisting applications, whereas the U.S. trend toward automation will emphasize the use of cemented carbides.

A surprising picture develops when comparing our forecasted demand with projected production. Since 1980 as many as 31 mines in Alaska and seven western states have produced tungsten ore, but the bulk of this tonnage came from only four mines in California, Nevada, and Colorado. Similarly, most future production can be expected here, too, although some may be developed in North Carolina. Annual U.S. production is estimated to reach about 9 million pounds by 2000. Total U.S. tungsten reserves have been estimated at 275 million pounds, which is substantially less than the expected demand of 741 million pounds, a shortfall of about 63 percent.

Colorado will figure prominently in domestic tungsten production as long as the molybdenum industry remains stable. As we have seen in the recent world recession, problems in the steel industry can drastically affect the molybdenum industry, which in turn impacts Colorado's tungsten and tin output as well as its mining industry. Climax contains possibly on the order of 15 to 20 percent of the country's tungsten reserves, a significant portion in light of the potential shortfall that could develop by the end of the century.

Looking at the other Colorado tungsten reserves (Table 3), one sees estimated reserves of about 450,000 units of WO_3, equivalent to about 7,225,000 lb of tungsten. About 70 percent of this (5 million pounds) is contained in the Boulder County district. The total from Boulder and other central and southwestern counties amounts to at most only about one-sixth of the Climax reserve though.

Factors that could affect the domestic tungsten industry and ultimately our seemingly large future reliance on foreign tungsten include (1) new photometric and chemical methods for tungsten recovery from low-grade ores and brines, (2) research in electrodeposition to extend the life of carbide materials, (3) possible substitution of ceramics in some high-temperature applications, and (4) advances in tungsten fabricability and improvement in tungsten-alloy preparation.

Tin

Tin was known and alloyed with copper to make bronze over 5000 years ago. Its largest present use is tinplate in the fabrication of metal containers for food, beverages, and other commodities. In the automotive industry tin is widely used for engine bearings and coatings, body finishing, and other parts. Tin finds widespread use as an alloy in solders, bronze and brass, castings, gears, electrical and electronic machinery. Tin chemicals find diverse use in plating, perfume and soap stabilizers, toothpastes, glass and plastics, and fungicides.

Tin is a relatively scarce element, and its only commercial source is the oxide, cassiterite. Some small quantities are recovered from complex sulfides of copper, lead, silver, tin, and antimony. Tin deposits generally occur as greisens associated with acidic igneous rocks irregularly distributed in a belt around the Pacific Ocean. Others occur in south-central Africa and along the east edge of the Atlantic Ocean. Most vein cassiterite ore is mined by conventional underground hard-rock methods. However, most tin is obtained from placer and eluvial deposits derived from the weathering of vein and disseminated deposits.

The bulk of the world's tin production comes from Thailand, Malaysia, China, Indonesia, Brazil, Bolivia, Zaire, United Kingdom, and the USSR. Minor domestic reserves lie principally in Colorado, Alaska, California, South Dakota, and Texas. Although the U.S. produces only a small fraction of the world's tin annually, it is the leading consumer of both primary and secondary (brass, bronze, solder, alloy, scrap) tin. The U.S. has only one primary tin smelter. Domestic production in recent years has come only (1) as by-product of molybdenum milling in Colorado and (2) from placer operations in Alaska and New Mexico.

Pegmatites are the source of Colorado's most well-known tin occurrences. The Devils Head area (Douglas County), St. Peters Dome (El Paso County), and Crystal Peak area (Teller County) all contain Precambrian pegmatites cutting the Pikes Peak granite batholith. Cassiterite occurs as an accessory mineral with zircon, topaz, fluorite, rare fluorine minerals, rare earths, and niobium minerals, many of which are collected for specimen value.

The principal tin vein occurrence lies in the Badger Flats area near Lake George (Park County), about 30 miles northwest of Colorado Springs. Precambrian metasedimentary rocks have been intruded by older Precambrian (X) granodiorite, younger Precambrian (Y) Silver Plume Granite, and still younger Precambrian (Y) Pikes Peak and Redskin Granites. The principal fissure veins contain quartz, barite, fluorite, beryllium, and tungsten. The district's characteristic greisens are pneumatolytically altered rocks presumably formed by gaseous emanations from the cooling Redskin pluton. The rock typically is composed of quartz and lithium mica, topaz, fluorite, and various trace elements (lithium, molybdenum, tin, tungsten, base metals).

Cassiterite in the Mary Lee mine at Badger Flats occurs as crystals in quartz cavities in a vein that cuts Boulder Creek granodiorite and the granite-aplite facies of the Redskin Granite. Semiquantitative spectrographic analyses of vein, altered granite, and greisen samples showed 0.0015 to 0.03 percent Sn, with a high of 0.15 percent in the greisen walls of a quartz vein (Hawley, 1969).

Colorado's pegmatite and vein cassiterite occurrences are of interest to mineral collectors and have no substantial economic potential.

The major economic tin occurrence in Colorado is the Climax molybdenum mine in Lake County. A stockwork molybdenite ore body is contained within the Tertiary composite porphyry intrusion. This deposit was described more fully in the chapter on tungsten. Cassiterite, tungsten concentrates (huebnerite and wolframite), iron pyrite, and monazite (formerly) are recovered as by-products of molybdenum milling. Although the grade of tin is rather low, only 0.002 to 0.006 percent, the large tonnages of ore milled annually permit economic recovery. In the last ten years, 156,000 to 200,000 lb of tin concentrates have been recovered annually. Over three million pounds have been recovered since 1953 (Table 4).

Estimated tin imports for 1983 amounted to 36,400 short tons of metal and 880 short tons of ore, compared to negligible U.S. mine production, 2,750 short tons of smelter production, and 16,530 short tons of secondary production from scrap detinning and nonferrous metal-processing plants. As of 11/30/83, the federal stockpile goal was 47,027 short tons. Inventory was 210,096 short tons, with 24,396 short tons of excess authorized for disposal.

Harris (1978) estimated the domestic demand for tin by 2000 to range from 32,000 to 89,900 short tons, with a probable expected demand of 68,300 short tons. This presents an annual growth rate of 0.4 percent. The growth rate for world tin demand is expected to range from 0.1 to 1.9 percent annually, with a probable growth rate of 1.3 percent; however, world tin reserves are sufficient to meet demand.

Carlin's (1981) and Harris' (1978) estimates of U.S. tin reserves are very close and represent lode and placer deposits mostly in Alaska (Seward Peninsula), Colorado, New Mexico, South Dakota, and Texas (Table 6). The U.S. holds only 0.7 to 0.8 percent of the world's total estimated reserves and 1.5 percent of other world resources. Sainsbury and Reed's (1973) figures are comparable to the others but have been subdivided into categories for both reserves and conditional and undiscovered resources. The tables show that the U.S. holds 45,000 to 55,000 short tons of tin reserves and an additional 165,000 to 170,000 short tons of other resources, but no breakdown by state was given.

Certainly U.S. tin resources fall far short of meeting the expected cumulative demand of 1,300,000 short tons by 2000; so, the country necessarily will import nearly all its primary tin requirements. Continued by-product tin recovery at the Climax Mine will, if not reduce our dependence on foreign tin, at least help maintain the present proportion of foreign reliance. However, with the recent turmoil in national and international steel markets and with greatly expanded non-tin-bearing molybdenum capacity in other areas, annual production at Climax in the next 20 years possibly may not attain its former noteworthy levels. Greater emphasis likely will be placed on expanded secondary recovery and recycling but only if peacetime economics permit.

Thorium

Thorium is similar to uranium in that it produces a series of radioactive decay products. However, it is more stable than uranium during weathering and tends to be less concentrated than uranium in its significant deposits. The first commercial use of thorium came in the late 1880s when it was found that gas lights and lamps burned brighter and steadier when surrounded by a mantle impregnated with a thorium compound. Since then, thorium has been used mainly in incandescent gas mantles. Its other important uses include high-temperature magnesium-base alloys for aircraft and aerospace, high-strength corrosion-resistant metals, oxides for catalysts in the chemical and petroleum industries, oxides and metal for radiation detectors, electric discharge tubes, computers, and tungsten welding rods, polishing compounds and drugs. An important future potential use for thorium is in the atomic energy industry. Thorium cannot be used directly in reactors because it lacks fissionable isotopes; however, neutron bombardment from fissionable U^{235} can convert thorium to fissionable U^{233}. This process was demonstrated in a prototype high-temperature gas-cooled reactor (HTGR) in 1966. The only commercial plant especially designed for the thorium-cycle HTGR process is

Table 6. Estimated U.S. tin reserves and resources compared to North America and rest of world. Figures converted to short tons from original sources (Sainsbury and Reed, 1973, Table 135; Harris, 1978, Table 3; Carlin, 1981, Table 3).

Sainsbury and Reed (1973):

	RESERVES			CONDITIONAL RESOURCES			UNDISCOVERED RESOURCES		
	Measured & Indicated	Inferred	Total	Paramarg.	Submarg.	Total	Hypoth.	Specul.	Total
U.S.	9,447	37,072	46,519	--	48,160	48,160	44,800	78,400	123,200
Canada, Mexico	12,320	16,800	29,120	15,680	15,680	31,360	--	277,424	277,424
Total N. America	21,767	53,872	75,639	15,680	63,840	79,520	44,800	355,824	400,624
Total World	4,087,961	7,087,136	11,175,097	6,594,560	4,897,760	11,492,320	10,403,680	8,405,264	18,808,944

Carlin (1981):

	RESERVES	OTHER RESOURCES	TOTAL RESOURCES
U.S.	55,100	165,300	220,400
Canada, Mexico	33,060	286,520	319,580
Total N. America	88,160	462,840	551,000
Total World	11,020,000	29,754,000	40,774,000

Harris (1978):

U.S.	44,080	165,300	209,380
Canada, Mexico	27,550	297,540	325,090
Total N. America	77,140	462,840	539,980
Total World	11,020,000	29,754,000	40,774,000

Public Service Company of Colorado's Fort St. Vrain generating plant at Platteville (Weld County). This type of reactor has important advantages over conventional uranium reactors, namely higher efficiency, cheaper fuel and less thermal pollution.

Historically the principal source of thorium has been the mineral monazite, a thorium and rare-earth phosphate found in fluviatile and beach sands and usually recovered in heavy-mineral concentrates along with rutile, ilmenite, zircon, and cassiterite. Most monazite is now recovered for its rare-earth content from placers in North and South Carolina. Thorium also occurs in uranium ores and in veins as the minerals thorite ($ThSiO_4$) and thorianite (ThO_2). Disseminated thorium and associated rare earths, titanium, columbium, and zirconium are especially characteristic of alkalic complexes and carbonatites associated with late-stage residual magmatic activity.

Colorado has produced minor amounts of thorium ore from veins in the Wet Mountains of Custer and Fremont Counties and in the Powderhorn or Iron Hill area of Gunnison County. Thorium contained in monazite concentrates was produced as a by-product of molybdenum milling at the Climax Mine in Lake County. Other minor vein occurrences are found in the Cochetopa district and Jacks Creek area (Saguache County), White Pine district (eastern Gunnison County), Park district (Hinsdale County), and with fluorite at Jamestown (Boulder County). Pegmatite occurrences were found in the Trout Creek area (Chaffee County), Clear Creek province (Jefferson County), and St. Peters Dome (El Paso County). Monazite in fossil placers occurs in the Mesaverde Group (Late Cretaceous) in Montezuma and Mesa Counties. In modern placers monazite has been and will be recovered in a gold placer operation in the Timberlake district near Craig (Moffat County).

The Powderhorn or White Earth district in southern Gunnison County is one of the most unusual and potentially most productive mineralized areas in Colorado. The district in the past has produced minor amounts of iron ore, vermiculite, and thorium, but is now known to hold large reserves of thorium, columbium, and titanium. Country rocks consist of Precambrian metavolcanics (Dubois Greenstone) intruded by the Precambrian Powderhorn and Tolvar Peak granitic plutons. This sequence is in turn intruded by the Late Precambrian or Cambrian Iron Hill alkalic complex of pyroxenite, uncompahgrite, ijolite, nepheline syenite, and massive carbonatite. Radial carbonatite dikes, peripheral thorium veins and trachyte dikes extend up to 10 miles north and northwest of the carbonatite stock. Part of the alkalic complex was intruded later by Cambro-Ordovician diabase dikes. The complex possibly was localized by late Precambrian movement on the northwest-trending Cimarron fault, which also shows Laramide movement. Thorium occurs in five distinct geologic environments (Hedlund and Olson, 1961; Olson and Hedlund, 1981).

Thorium veins cut the older granitics and Dubois Greenstone south, west, and northwest of the complex. Discontinuous veins generally less than one foot thick commonly lie in anastomosing, steeply dipping shear and breccia zones up to 10 ft wide. Orthoclase partly replaces the wall rocks adjacent to most veins, which contain sporadic base-metal sulfides, rare earths, rutile, apatite, fluorite, barite, and vanadinite. The thorium occurs as thorite and thorogummite (complex Th-U-rare earth silicate) intergrown with iron oxides.

Discontinuous trachyte and trachyte porphyry dikes follow local joints and fractures in the Dubois Greenstone, older metamorphics, and peripheral granites. Lath-shaped orthoclase phenocrysts lie in a trachytic aphanitic groundmass of orthoclase microlites. Thorite and thorogummite appear to be concentrated in hematite pseudomorphs after pyrite.

Thorium occurs in perovskite and apatite within magmatic segregations of magnetite-ilmenite-perovskite, the principal ore material for titanium here. A fourth occurrence is dissemination in small, irregular, fine-grained, partly fenitized granitic plutons and dikes south and west of the complex.

The last principal occurrence is in carbonatite. The massive carbonatite stock at Iron Hill has been called the country's largest reserve of columbium, contained in the mineral pyrochlore. The stock also contains significant amounts of rare earths and thorium and consists principally of dolomite, ankerite, siderite, calcite, pyrochlore, fluorspar, magnetite, ilmenite, hematite, goethite, pyrite, rutile, zircon, and barite. The thorium in part occurs in monazite and pyrochlore. Some apparently has been found in weakly radioactive jasper in silicified fracture zones and in strongly radioactive martite-apatite veins. Thorium appears to be more concentrated in the carbonatite dikes that cut the adjacent pyroxenite and uncompahgrite. In the most radioactive dikes layers of siderite and ankerite alternate with dolomite, calcite, or biotite. The dikes, like the stock, also contain pyrite, moderate to small amounts of barite, apatite, monazite, quartz, bastnaesite, and synchisite. The less radioactive dikes are more homogeneous and contain only sparse pyrite and apatite. In both, thorium apparently is contained, at least in part, within the monazite.

The Wet Mountains of Fremont and Custer Counties, south-central Colorado, are the site of the State's second principal thorium province, a 38-mile-long area extending from the Arkansas River southeast to Rosita. Thorium deposits are spatially and genetically related to a cluster of three Cambrian alkalic complexes. The first, McClure Mountain, lies 11 to 17 miles southwest of Canon City in Fremont County and consists of olivine gabbro, anorthosite, pyroxenite, and dunite with a syenitic complex of biotite-hornblende syenite, nepheline syenite, and mafic nepheline-bearing rocks. The complex shows a crude zonation with older mafic and ultramafic rocks on the periphery and younger nepheline-bearing rocks in the center. The Gem Park complex, 21 miles southwest of Canon City on the Fremont-Custer County line, consists of pyroxenite and gabbro of varying textures intruded by carbonatite dikes containing columbium, rare earths, and copper-nickel-iron sulfides. In the Democrat Creek complex, also on the Fremont-Custer County line 15 miles southwest of Canon City, Precambrian metasedimentary and granitic gneisses and migmatite were intruded by a composite quartz-syenite stock and explosion breccias.

The country rocks and alkalic rocks in these areas were intruded by younger red syenite dikes and thorium-bearing quartz-feldspar-barite veins. Anomalous thorium also occurs in the carbonatite dikes, fracture zones, and enveloping fenites. Coarse-grained carbonatite up to 9 ft thick occurs as discontinuous elongated lenses within 4 miles of each complex. The mineralogy is substantial--calcite, dolomite, sparse ankerite and strontianite, quartz, hematite, barite, pyrochlore, fluorite, base-metal sulfides, and other rare-earth minerals such as monazite, bastnaesite, synchisite, xenotime, and fluorapatite. Primary carbonatite dikes contain an average 0.17 percent ThO_2, 0.0097 percent Nb_2O_5, 0.0031 percent U_3O_8, and 2.15 percent rare-earth oxides.

Fracture zones 3 to 4 ft wide cut the generally northeast- to east-northeast-trending metamorphic foliation along a persistent northwest trend. Many contain several types of dike and vein material, often overlapping and grading into one another. Carbonatite may replace lamprophyre or red syenite, and quartz-feldspar-barite veins may intersect carbonatite. Vein and fracture samples contained an average 0.46 percent ThO_2 and a maximum 0.036 percent uranium, with an average Th:RE ratio of 2.2.

Various reserve and resource estimates have been made for thorium in the Wet Mountains and Powderhorn areas by Staatz and others (1979, 1980) and Olson and Hedlund (1981) and are summarized in Tables 7 and 8.

For the Wet Mountains Staatz and others (1979, 1980) estimated thorium reserves for the seven largest carbonatites and subdivided the estimates on the basis of total production costs per pound, based on similarity with uranium production. Total cost per pound includes development, plant and equipment, operating, and mill costs. The deposits are assumed to be minable by the cut-and-fill method, accessible via vertical shaft with connecting drifts. Ore would be mined from successive equally spaced intervals. In addition to thorium, these carbonatites contain the following recoverable coproducts (Staatz and others, 1980) (figures in short tons):

	U_3O_8	Nb_2O_5	RE Oxides
Reserves	17	40	2,500
Probable Potential Resources	105	228	14,300
Total	122	268	16,800

Table 7. Estimated thorium reserves and probable potential resources in the Wet Mountains (figures in short tons). Carbonatite estimates are from Staatz and others (1980); vein/fracture estimates are from Staatz and others (1979).

	Reserves	Probable Potential Resources	Producible at	Grade
CARBONATITES:				
3 carbonatite dikes	92	531	\$15-\$30/lb	
4 carbonatite dikes	39	222	\$50/lb	
Subtotal	131	753		0.17 % ThO_2
VEINS/FRACTURES:				
10 veins	54,100	141,000	< \$15/lb	0.15 % ThO_2
6 veins	2,540	10,100	\$15-\$30/lb	
4 veins	7,280	8,880	\$30-\$50/lb	0.11 % ThO_2
Subtotal	63,920	159,980		
TOTAL	64,200	160,500		

For veins and fractures, the cost breakdown was based on 29 vein systems whose reserves and resources totaled at least 35,000 short tons. A slight discrepancy exists between the total vein reserves and resources figures given and the totals of the individual vein categories (from Staatz and others' original table).

Table 8. Estimated thorium reserves and probable potential resources in the Powderhorn (Iron Hill) district (figures in short tons). Reserve figures are from Olson and Hedlund (1981, Table 4); resource figures for massive carbonatite are from Staatz and others (1979, 1980).

		Reserves		Grade
	Indicated	Inferred	Subtotal	(ppm ThO_2)
10 Carbonatite Dikes	100	200		>1000
	500	1,000		500-1000
	700	1,000	3,500	100-500
56 Veins	1,800	7,900		>1000
	200	600		500-1000
	1,400	3,800	15,700	100-500
Carbonatite Stock	30,000	110,000	140,000	41
Magnetite-perovskite rock	0	25,000	25,000	±250
Fine-Grained Granite	5,000	9,000	14,000	>100
Total	39,700	158,500	198,200	

			Potential Resources		
	Carbonatite	ThO_2	U_3O_8	Nb_2O_5	Rare-earth Oxides
Massive Carbonatite (above ground)	772,700,000	31,080	9,180	411,900	2,865,500
Massive Carbonatite (to 800-ft depth)	2,672,000,000	114,900	33,930	1,523,000	10,590,000
Massive Carbonatite (minable to 800 ft)	2,030,000,000	87,300	25,800	1,160,000	8,050,000
13 Carbonatite Dikes*	--	4,240	287	6,590	106,000

* whether or not these 13 dikes include the 10 dikes above is uncertain.

Staatz and others (1979, 1980) defined several categories of potential resources within the massive Iron Hill carbonatite. Their first estimate is for carbonatite within the hill above the surrounding ground surface and containing an average grade of 0.0043 percent ThO_2, 0.057 percent Nb_2O_5, 0.00127 percent U_3O_8, and 0.397 percent rare-earth oxides, based on 151 measurements for Th and analytical data for 28 samples for the other coproducts. Because the distribution of these elements within the stock is erratic, higher grades could be obtained through selective mining. The amount of carbonatite within the hill could be classified as reserves because its actual dimensions and average grade are known. Extending the probable resources to a minable depth of 800 ft gives a total ore tonnage in excess of 2.5 billion short tons. An open pit mining operation would remove all of the hill and a conical-shaped body of carbonatite below the surface. At an assumed overall pit slope of 1:1, the minable ore decreases to about 2 billion tons. The estimated ThO_2 contained in this category could be mined at a cost less than $15/lb if the niobium, uranium, and rare earths are recovered as coproducts; otherwise, the cost would exceed $50/lb.

Olson and Hedlund (1981) estimated the carbonatite stock to contain about 140,000 short tons ThO_2 reserves at a grade of 41 ppm ThO_2 and to a depth of 804 ft (245 m, their figure). Their indicated reserves of 30,000 short tons correspond to Staatz and others' "above-ground" estimate. They also presented reserve estimates for magnetite-perovskite rock and for disseminated thorium in the fine-grained granite plutons, both based on a limited number of analyses. Figures for carbonatite dikes include only ten that were evaluated. The total with other dikes is probably at least several times the amounts shown. For the vein deposits, total indicated and inferred reserves at grades greater than 500 ppm ThO_2 were subdivided on the basis of total production costs per pound, as shown below:

Vein Reserves (short tons)	$30/lb	Producible at $30-$50/lb	$50/lb
2,000 Indicated	1,600	200	200
8,500 Inferred	7,700	700	100

Olson and Hedlund thus estimated a total of nearly 200,000 short tons ThO_2 reserves in the various types of thorium-bearing deposits for the district, including the hill portion of the carbonatite stock.

The importance of Colorado's thorium resources in these two provinces can be emphasized by comparing the resources with others in the U.S. for which estimates have been calculated (Table 9). Four massive carbonatites are known in the country--Powderhorn (Colorado), Sulphide Queen (California), Magnet Cove (Arkansas), and Elk Creek (Nebraska). Staatz and others (1979) did not evaluate the Arkansas carbonatite because it contains no thorium. Neither was the Elk Creek carbonatite evaluated because of the lack of information. Comparing the Powderhorn and Sulphide Queen deposits, the estimates show that Colorado holds 75 percent of the known reserves and over 90 percent of the probable potential resources, assuming corecovery of uranium, columbium, and rare earths. Staatz and others (1980) evaluated carbonatite dikes in three areas--Powderhorn and Wet Mountains Colorado, and Mountain Pass, California. Smaller unevaluated resources are known in Idaho, Montana, and Arkansas. Colorado holds over 90 percent of both the reserves and probable potential resources of thorium in carbonatite dikes.

Principal thorium vein districts include Wet Mountains and Powderhorn (Colorado), Lemhi Pass, Hall Mountain, and Diamond Creek (Idaho), Bear Lodge Mountains (Wyoming), and Mountain Pass (California). Colorado holds nearly 50 percent of both the reserves and probable potential resources of thorium in veins.

Table 9. Comparison of estimated thorium reserves and probable potential resources in Colorado with other U.S. sources (figures in short tons) (from Staatz and others, 1979, Tables 2 and 3; 1980, Table 8).

	Reserves	Probable Potential Resources
VEINS:		
Wet Mountains	64,200	160,500
Powderhorn	1,900	8,500
Total Colorado	66,100	169,000
Total Other U.S. Sources	75,665	174,075
Total U.S.	141,765	343,075
% in Wet Mountains	45.3	46.8
% in Powderhorn	1.3	2.5
% in Colorado	46.6	49.3
CARBONATITE DIKES:		
Wet Mountains	131	753
Powderhorn	763	4,240
Total Colorado	894	4,993
Total Other U.S. Sources	84	486
Total U.S.	978	5,479
% in Wet Mountains	13.4	13.7
% at Powderhorn	78.0	77.4
% in Colorado	91.4	91.1
MASSIVE CARBONATITE:		
Powderhorn	31,080	114,900
Total Colorado	31,080	114,900
Total Other U.S. Sources	9,750	9,750
Total U.S.	40,830	124,650
% at Powderhorn	76.1	92.2

Most of our thorium imports come from France, Netherlands, Canada, United Kingdom, and Malta and in 1981 amounted to 554 short tons. Most of this was contained in Australian monazite concentrates, which were not processed for thorium. Actual ThO_2 contained in imported compounds, metals, alloys, and gas-mantle oxide equivalents was about 55 short tons for 1981. As of 11/30/83, the federal stockpile goal for thorium (as nitrate) was 143 short tons. Inventory was 1,705 short tons with 1,448 short tons excess authorized for disposal.

Kirk (1981) estimated the domestic demand for thorium from 1978 to 2000 to range from 57 to 220 short tons annually, with a probable expected demand of 155 short tons by 2000, representing a probable average growth rate of 7.3 percent. Cumulative domestic demand is expected to reach 1,800 short tons by 2000. The growth rate for the rest of the world is expected to reach an average of 8.2 percent by 2000, with a cumulative demand of 10,800 short tons. Although projected U.S. production will be less than primary demand in 1990 and 2000, domestic reserves are sufficient to meet the cumulative demand. Looking at thorium-fueled electric generating plants, the low forecast demand of 10 short tons for such plants assumes only a few additional plants. The high forecast of 100 short tons assumes a thorium-fueled generating capacity of 12,000 MW and shortages of uranium due to less successful exploration efforts. The probable forecast demand of 20 short tons is based on a total of six to ten thorium-fueled plants with a total generating capacity of 8,000 MW.

The rest of the world's thorium demand may be substantially higher than the United States' assuming that both countries containing abundant thorium reserves and those with neither uranium nor thorium place greater emphasis on thorium-fueled reactors. A similar increase in thorium demand for this use in the U.S. may not occur until the federally imposed suspension of reprocessing and recycling of commercial nuclear fuels is removed. Thorium demand is not expected to increase significantly for such nonenergy uses as gas mantles, refractories, welding rods, and aerospace alloys.

The economics of thorium recovery from Colorado deposits dictate coproduct recovery with other important commodities--uranium, columbium, and rare earths. At Powderhorn thorium in the massive carbonatite could be recovered as a coproduct (along with uranium, columbium, rare earths, and vanadium) in an attendant operation of titanium (perovskite) mining.

Columbium (Niobium)

Columbium is an essential element in superalloys used in jet and turbine engines and in columbium carbide, one of the hardest known substances, for machine cutting tools. As the key ingredient in high-strength low-alloy steel, it is used in a wide variety of specialty end uses including beams and girders in buildings and offshore drilling towers, special industrial machinery, oil and gas pipelines, railroad equipment, ships plate, and automobiles. Uses in nuclear and aerospace applications and as electrical superconductors at cryogenic temperatures are minor but have tremendous growth potential.

Columbium is a silvery gray, lustrous refractory metal with about the same hardness and specific gravity as copper. Characteristics include a high melting point (2480°C), resistance to corrosion and ease of fabrication, but poor resistance to oxidation. Columbium usually occurs with varying amounts of tantalum in two isomorphous series of ore minerals -- columbite-tantalite and pyrochlore-microlite.

In 1981 about 98 percent of the free world's columbium production came from Brazil (ferrocolumbium and columbium oxide) and Canada (pyrochlore concentrates). Other significant producers include Nigeria (columbium concentrates), Thailand and Malaysia (columbium-bearing tin slags), Australia, Zaire, and the USSR. The bulk of the world's reserve base (reserves - marginal reserves + subeconomic resources) is contained in the following countries (in descending order): Brazil, USSR, (U.S.), Canada, Nigeria, Zaire, Thailand, and Malaysia (Cunningham, 1983).

Colorado previously ranked fourth in output of domestic columbium-tantalum concentrates, having produced about 20,000 lb through the early 1960s (Parker, 1968). This represents only about one percent of the country's total production, which itself has been only a small fraction of total world production. Colorado's only previous commercial source of columbium (and tantalum) has been from columbite and tantalite in pegmatites, although columbium-bearing rare-earth minerals (euxenite, samarskite, and fergusonite) and microlite also have been marketed. Table 10 lists the principal pegmatites in which columbite and tantalite are known to occur and from which some has been produced, including pertinent accessory mineralogies and reserves. The principal mineralogies of all the deposits are quartz, muscovite and/or biotite, and various feldspars (albite, microcline, cleavelandite). The columbite or columbite-tantalite from the productive deposits generally occurs with beryl, garnet, tourmaline, lithium minerals, microlite, and some bismuth and uranium. In most deposits recovery of columbite-tantalite would depend on corecovery with beryl, mica, microlite, and feldspar.

The Powderhorn alkalic complex (described earlier in the section on thorium) represents the largest single domestic columbium reserve, along with a large reserve of titanium. The principal columbium carrier is a foliated carbonatite stock in which pyrochlore occurs with fine granular apatite along shear planes and replaces carbonate along grain boundaries. Columbium is also concentrated in weathered carbonatite dikes related to the stock, in magnetite-perovskite bodies and in thorium veins and related potash feldspar-rich rock. In the magnetite-perovskite bodies columbium occurs in perovskite, but in the silica-rich thorium veins, it is concentrated in columbite.

Buttes Gas and Oil Company currently holds mining claims and patents in the area. Company reports indicated the deposit theoretically contained 1.4 billion lb (700,000 short tons) of recoverable columbium oxide (Cb_2O_5) with an in-place value of more than $5 billion based on high-purity oxide priced at $3.50/lb. The company has proposed to extract 1,925 short tons of high-purity columbium oxide annually with gross revenues of nearly $10 million. However, the project has still not materialized.

The third major occurrence of columbium is columbite and pyrochlore in the Cambrian-age Gem Park alkalic (pyroxenite-gabbro) complex on the Fremont-Custer County line, 21 miles southwest of Canon City. The pyrochlore occurs in dolomite-blue amphibole-pyrochlore carbonatite dikes characterized

Table 10. Principal columbium/tantalum-bearing pegmatites in Colorado, listing pertinent accessory mineralogies, reported approximate production and reserves, in pounds (compiled from Hanley and others, 1950).

			Cb-Ta	
County	Mine/Prospect	Accessories	Prod.	Reserves
Boulder	Beryl No. 1	beryl		small
	New Girl	beryl		
Chaffee	Mica-Beryl	beryl	5	
Clear Creek	Grover	beryl, bertrandite, fluorite, monazite		small
Fremont	Devils Hole	beryl, tourmaline, garnet, magnetite, apatite, Bi	200	100,000
	Meyer	beryl, tourmaline, garnet, lepidolite, amblygonite		small
	Mica Lode	tourmaline, garnet, apatite, beryl, triplite, Bi	615	small
	Phantom Canyon	beryl, garnet		
Gunnison	Brown Derby	lepidolite, beryl, topaz, fluorite, tourmaline, garnet, microlite, monazite, gahnite, betafite	small (Ta)	small
	Opportunity # 1	lepidolite, topaz, beryl, microlite		small
	White Spar # 1	lepidolite, microlite, beryl, topaz, tourmaline		
Jefferson	Bigger	tourmaline, beryl, monazite, bismuthinite, uraninite		
Larimer	Buckhorn	beryl, tourmaline, spodumene		small
	Crystal Silica	beryl, apatite, garnet		
	Tantalum	beryl, tantalite (76 % Ta_2O_5 and 10 % Cb_2O_5)		small
Park	Meyers Ranch	beryl, garnet, tourmaline, apatite, Bi	2000	30,000-60,000

by fibrous blue crocidolite and thorium-bearing pyrochlore. The columbite occurs in a similar dike and in a carbonatite dike outside the complex. Both minerals also are present as rare accessories in dolomite-barite-monazite carbonatite dikes. Columbium also occurs (1) with titanium in the thorian variety of perovskite known as irenite; (2) in the crystal lattice of vermiculite and (3) in ilmenite, rutile, and anatase. In addition the rare niobate, lueshite ($NaNbO_3$), was first reported from the Vermiculite Mine area in this district. The mineral contains thorium and uranium and can be found (1) enclosed in vermiculite books forming clusters with pyrochlore, ilmenite, and thorianite, (2) in fine fibrous amphibole-carbonate material interstitial to vermiculite books, and (3) as cubes and clusters in narrow black serpentine dikelets.

Despite the variety of columbium-bearing minerals, the carbonatite dikes offer little potential for economic recovery due to their small size, discontinuity, and variable grade, although locally the grades do approach minable levels of 0.02 to 0.7 percent. Greater potential lies, however, in the possibility of a buried carbonatite body postulated to lie beneath the fenitized rock at the Vermiculite Mine.

Columbium imports have decreased from 3,800,000 lb of concentrates and 5,900,000 lb of ferrocolumbium in 1980 to an estimated 1,300,000 lb of concentrates and 2,000,000 lb of ferrocolumbium in 1983. Since U.S. production in those years has been only small unreported amounts of columbium-tantalum concentrates from South Dakota, all domestic consumption has been imported primarily from Brazil and Canada. Nine plants in the U.S. process imported raw materials into columbium metal, carbide, ferrocolumbium, oxides, and nickel columbium.

As of 11/30/83, the federal stockpile goals were 100,000 lb of carbide powder and 5,600,000 lb of concentrates. Total inventories were 21,000 lb of carbide powder, 937,000 lb of concentrates, 598,000 lb of ferrocolumbium, and 45,000 lb of metal. None of the excess metal and ferro have been authorized for disposal. In addition the stockpile contains 869,000 lb of non-stockpile-grade concentrates and 333,000 lb of non-stockpile-grade ferrocolumbium.

Cunningham (1983) estimated domestic columbium demand from 1981 to 2000 to range from 14,000,000 to 26,000,000 lb, representing a probable demand of 18,000,000 lb by 2000 or an average annual growth rate of 5.1 percent. Probable cumulative demand by 2000 is estimated to be 233,000,000 lb. The rest of the world is expected to see a similar growth rate, with a cumulative demand of 681,000,000 lb by 2000.

Domestic columbium resources include Idaho and Oklahoma placers, Arkansas bauxite, alumina-plant wastes, and the Iron Hill carbonatite stock and related alkalic rocks at Powderhorn. The Iron Hill stock is considered to be the country's largest single columbium reserve. Drilling by DuPont in the late 1950s indicated a minimum 100,000 short tons of ore at an average grade of 0.25 percent Nb_2O_5, with a substantial amount at 0.35 percent Nb_2O_5. Thompson (1983) recently estimated 36 to 40 million short tons of ore at an average grade of 0.25 percent Nb_2O_5 contained in the largest carbonatite bodies. Referring to Table 8 in the section on thorium, we see that Staatz and others (1979, 1980) estimated that the 773 million short tons of massive carbonatite within Iron Hill contained 411,900 short tons of Nb_2O_5. Assuming the stock to be minable by open pit to a depth of 800 ft, the potential resource increases to 2 billion short tons of carbonatite containing 1,160,000 short tons of Nb_2O_5. A small additional amount would be recoverable with thorium from the district's principal carbonatite dikes.

Although Buttes' primary target is titanium from the perovskite-bearing pyroxenite, the company was considering (as of August 1983) corecovery of columbium and rare earths. However, near-term plans for columbium recovery have not been developed. Even if the carbonatite is processed separately from the titanium operation, economic recovery likely will depend on coproduct recovery of thorium, uranium, and rare earths.

No reserve estimates were found for columbium in the Gem Park carbonatites. Estimates were made of columbium and tantalum only for several of the State's pegmatite deposits and show only small recoverable quantities, usually contingent on corecovery with other pegmatite minerals.

Titanium

The major industrial uses for titanium have come about only in the last century. In its various industrial applications titanium is used both in metallic form as sponge metal and as a nonmetallic dioxide. Over one-half the sponge metal the U.S. fabricates from imported ores, concentrates, and scrap goes into aircraft as engine components and mainframe structures and into missile assemblies and spacecraft. Its high strength-to-weight ratio and strength at high temperatures make titanium advantageous as an alloy. The remaining sponge metal is consumed in components for oil, chemical, and electrochemical processing and power generation because of its resistance to corrosion, especially in a chloride-ion (marine) environment. Titanium's potential critical markets include offshore drilling-platform structures, sour-gas well-drilling equipment, ocean thermal energy-conversion heat exchangers, and nuclear waste storage.

Over 90 percent of titanium dioxide production is consumed in surface coatings--paint, varnish, lacquer--because of its opacity, whiteness, and brightness. For the same qualities, titanium pigments find use as coatings and fillers in paper. Other important uses include welding-rod coatings, plastics, floor coverings, roof coatings, tires, ceramics, and coated fabrics. Titanium carbide substitutes for tungsten carbide in industrial cutting tools.

Titanium, the ninth most abundant element, usually occurs chemically combined with oxygen or iron. Commercial ores may contain ilmenite ($FeTiO_3$), its alteration product, leucoxene (indefinite composition but closely related to sphene or titanite, $CaTiSiO_5$), rutile (TiO_2), and potentially perovskite ($CaTiO_3$). Because domestic rutile occurs in economically marginal or submarginal deposits, our requirements are entirely imported, mostly from Australia, South Africa, Sri Lanka, and Sierra Leone, although some has been mined in Arkansas and Virginia. Primary rutile occurs in alkalic igneous complexes, alkalic noritic-anorthositic complexes, granitic to syenitic veins and pegmatites, and alumina-rich high-grade metamorphic rocks. Of more importance are secondary rutile deposits--marine and stream placers and lag saprolites--all derived from the weathering of lower-grade primary deposits. Terrace and shoreline placers also contain other valuable heavy minerals, such as ilmenite, zircon, and monazite. The most important domestic rutile resources are fossil beach placers in Florida, Tennessee, and Georgia.

Ilmenite, more abundant than rutile, is commonly associated with primary vanadium-bearing titaniferous iron ores (hematite, magnetite) in gabbros, anorthosites, and amphibolites. Secondary ilmenite and heavy-mineral deposits mined in the U.S. include Cretaceous-Tertiary fossil placers in Florida and New Jersey, which yield ilmenite, rutile, and zircon. Principal ilmenite reserves occur in Florida, New York, and Tennessee, although the reserve base includes New Jersey, Oklahoma, Virginia, and Georgia.

The picture of domestic titanium production, imports, and ultimate reliance is complicated by a number of factors: (1) the U.S. produces ilmenite ore and concentrates and minor rutile; (2) synthetic rutile is produced from ilmenite; (3) pigments are produced from ilmenite and imported titanium slag (sulfate process) and from rutile and titanium tetrachloride (chloride process); (4) titanium sponge metal is produced from imported natural rutile, synthetic rutile, and tetrachloride; (5) titanium scrap is recycled for metal production.

Table 11 is a summary of production and consumption of ilmenite, metal and dioxide for 1981-1983. For pigments, imports have increased since 1980, but exports also have increased, doubling, in fact, since 1978. Fluctuating domestic production and apparent consumption have led to a variable import reliance from 3 percent in 1980 to 12 percent in 1982. Due to the depressed commercial aircraft industry, sponge metal production has dropped since 1979. Imports and exports (mainly scrap) also decreased. Thus the net import reliance decreased from 16 percent in 1980 to an estimated 9 percent in 1982. Ilmenite production in 1982 was less than half of that in 1981. Although consumption decreased, imports increased. So, net import reliance increased from 32 percent in 1980 to 75 percent in 1982. That for 1983 likely will be even higher.

Table 11. U.S. Production and consumption of ilmenite, sponge metal, and titanium dioxide for 1981-83 (compiled from U.S. Bur. Mines Mineral Commodity Summaries 1984). Figures in thousand short tons. W=withheld; NA=not available; e=estimated.

	Ilmenite			Sponge Metal			Dioxide		
	1981	1982	1983e	1981	1982	1983e	1981	1982	1983e
Production	542	263	220	26.4	15.6	13	761.2	635.1	735
Imports for Consump.	505	596	560	6.5	1.4	1.4	124.9	138.9	160
Exports	NA	19	10	9.6	8.1	7.7	61.1	72.8	85
Apparent Consump.	1133	1055	W	31.6e	17.3e	15	806	716.4	814
Reported Consump.	1109	809	900	--	--	--	--	--	--
Net Import Reliance as % of apparent consumption	52	75	W	16	9	W	6	12	10

As of 11/30/83, the federal stockpile contained no ilmenite. Total inventories of primary stockpile-grade titanium amounted to 21,465 short tons, considerably below the goal of 195,000 short tons. In October 1983 the GSA awarded contracts for the purchase of 4,500 short tons of primary titanium, to be completed by 9/2/84. The stockpile also contains 10,866 short tons of non-stockpile-grade sponge metal.

The only titanium produced in Colorado was as an undesirable contaminant of iron ores mined in the late 1800s. Several deposits, however, warrant mention, and one unusual deposit holds great future potential as a major domestic reserve. Minor titanium occurrences are reported in base- and precious-metal veins in several mining districts located near volcanic centers: Cripple Creek (Teller County), Bonanza (Saguache County), and Uncompahgre (San Juan County). Others are found in veins and pegmatites at St. Peters Dome (El Paso County) and Mt. Antero (Chaffee County).

The state's principal rutile deposit straddles the Clear Creek-Jefferson County line in the Front Range about 20 miles west of Denver. Just northwest of Bergen Park the Precambrian crystalline complex contains an east-west-trending sequence of folded metasedimentary gneisses of the upper amphibolite facies. The host rock is an 11- to 100-ft-thick, lenticular, sillimanitic topaz-quartz gneiss over 7000 ft long. The rutile is concentrated in thin layers of pale red, splendent crystals, especially abundant in apatite-rich stringers, with intergrown postmetamorphism topaz and prismatic sillimanite. Sheridan and others' (1967) samples showed up to 4.2 percent rutile with a maximum 67 percent topaz. A possible origin for this rock is fluorine metasomatism, in which sillimanitic quartz-rich gneiss was attacked by hot, fluorine-rich solutions, removing the common elements and minerals to leave a resistant assemblage of zircon, quartz and prismatic sillimanite, and adding rutile, topaz, and apatite. Although incompletely tested, the deposit holds some potential for rutile recovery with corecovery of topaz and sillimanite for refractory use. Marsh and Sheridan (1976) indicated a resource of 128,800 short tons of rutile recoverable from an average 40-ft-thick gneissic unit extending to a depth of 240 ft and having a grade of 2.1 percent rutile, 28.5 percent topaz, and 12.3 percent sillimanite (Table 12). An additional 52,640 short tons of rutile are inferred to exist within the next 100-ft interval of depth.

Table 12. Estimated titanium (rutile) resources in the Bergen Park area, tabulated from Marsh and Sheridan (1976, p. 16). Figures given in short tons, calculated from reported estimates in metric tons.

	Indicated Resources (to 240-ft depth)	Incremental Inferred Resources per 100-ft depth
sillim. topaz-quartz gneiss	6,160,000	--
rutile	128,800	52,640
topaz	1,792,000	723,520
sillimanite	750,400	313,600

The more significant titanium resources in Colorado occur as titaniferous magnetite, namely at Caribou (Boulder County), Iron Mountain (Fremont County), and Powderhorn (Gunnison County). The Caribou district, 36 miles northwest of Denver, produced gold and silver as early as 1870. Here the Tertiary-age Caribou monzonitic stock intruded Precambrian metamorphic rocks. Mafic variants of the stock include pyroxenite, hornblendite, biotite amphibolite, biotite pyroxenite, magnetite pyroxenite, magnetite peridotite, and titaniferous magnetite (Lovering and Goddard, 1950). The main magnetite ore body is a dikelike mass about 1500 ft long, containing intergrowths of diopside, magnetite, and ilmenite, and cut by magnetite stringers. Geophysical tests suggest that the body may extend to substantial depths. Analyses show high-grade ore at 4.5 percent TiO_2 and 65 percent magnetite and low-grade ore at 2.6 percent TiO_2 and 30 percent magnetite. No reserves apparently have been estimated.

On the periphery of the McClure Mountain alkalic complex in the Wet Mountains 12 miles southwest of Canon City, titaniferous magnetite was mined for iron ore as early as 1872. At the Iron Mountain Mine, Precambrian granitic and metamorphic rocks have been intruded by a funnel-shaped mafic-ultramafic sequence that in turn has been intruded by the outer syenite of the McClure Mountain complex. Discordant intrusives cutting the sequence include coarse- and fine-grained pyroxenite (peridotite and gabbro) and anorthosite.

Shawe and Parker (1967) found microscopic and megascopic ilmenite intergrown with compact aggregates of magnetite, which comprise up to 67 percent of the rock but commonly only about 5 to 10 percent. Rutile and spinel are associated with the magnetite. The iron ore originally was used in the blast furnaces probably at Pueblo, but by 1890 this use was discontinued undoubtedly because of the high undesirable titanium content. However, the ore was found useful as a "fix" or "fettle," a material such as ore, cinder, or scrap used to line the bottoms of open-hearth furnaces and puddling mills. The last reported use of the Iron Mountain ore was as a heavy aggregate for ballast. Although the average grade of the ore ran 12.95 percent TiO_2, no estimates of the available tonnage apparently have been made.

Colorado's largest, most significant titanium resource is found at Iron Hill in the White Earth district near Powderhorn, southern Gunnison County. the composite alkalic stock, described previously, consists of pyroxenite, uncompahgrite, ijolite, nepheline syenite, and massive carbonatite. Although ilmenite is abundant here, the primary ore mineral is perovskite, the calcium titanate not previously considered a titanium ore. The ilmenite and perovskite occur as magmatic segregations primarily in the pyroxenite and secondarily in uncompahgrite and ijolite. The randomly distributed segregations and dikes may contain relatively pure perovskite, magnetite-perovskite, or magnetite-ilmenite-perovskite. Even the gangue minerals, augite and biotite, are titaniferous enough to be considered of commercial value. In the near-surface oxidized zone the perovskite has altered to leucoxene. Perovskite and accessory apatite are enriched in niobium (columbium) and rare earths, which are most concentrated to the west in the massive carbonatite stock and carbonatite dikes. The principal ore zone is defined on the northeast by the contact with the Powderhorn Granite and on the southwest by the extent of coarse-grained pyroxenite, in which the higher grades appear to be limited. The zone measures 2.4 miles in length, about 0.4 miles in width, and at least 1000 ft in depth, with an average grade of about 12 percent TiO_2 (Thompson, 1983). The magnetite segregations also contain potentially recoverable vanadium and thorium (substituting for Ca in the perovskite).

Prompted by the high grades and the apparent large available tonnage, the Humphreys Engineering Company, who controlled the property in the 1950s, developed a technique for producing perovskite concentrates. The intimate intergrowth of perovskite with the magnetite is not conducive to separation. Under the exploration and development program of the current owner, Buttes Oil and Gas, research continues toward the production of synthetic rutile and pigments directly from perovskite.

Buttes' proposed beneficiation technique shows that a uniform-grade (20 percent TiO_2) preconcentrate as coarse as 20 mm could be recovered. In a preconcentrator coarse and fine dry magnetic cobbers and coarse and fine wet jigs could recover relatively pure perovskite and magnetite-perovskite. These preconcentrates would pass to a fine concentrator where a 0.5-mm grind would liberate both perovskite from magnetite-perovskite and some of the impurities from the perovskite. The ground pulp would proceed to permanent-magnet separators, yielding a 10-percent-TiO_2 magnetite concentrate. The nonmagnetic fraction (perovskite, augite, fine mica, and apatite) would pass through a spigot-type classifier, then to concentrating tables to yield a 30- to 40-percent-TiO_2 concentrate. Following dewatering and drying, high-tension electric separation could produce a +50-percent-TiO_2 concentrate (Thompson, 1983).

In the company's economic model a pigment plant probably would not be built at the mine. Concentrates would be shipped to a chemical plant that uses an HCl digestion process, ultimately yielding pigment-grade TiO_2 (Thompson, 1983). All the technical problems have not, however, been solved.

Buttes' economic model necessitates rare-earth recovery from soluble compounds in the process solutions. It is conceivable that the plant also could process columbium ore from the massive carbonatite as an attendant operation, although no such near-term plans have been devised. The open pit perovskite mine would be operated at 14,600 short tons daily (4,380,000 short tons annually), yielding 350,000 short tons of +50-percent-TiO_2 concentrates and 5,250 short tons of rare earths.

Lynd (1983) estimated domestic titanium metal (primary and secondary) demand from 1981 to 2000 to range from 42,000 to 83,000 short tons, representing a probable demand of 61,000 short tons by 2000, or an average annual growth rate of 5.0 percent. Domestic nonmetal demand for 1981 to 2000 is estimated to range from 650,000 to 1,200,000 short tons, representing a probable demand of 830,000 short tons by 2000. Cumulative demand for primary metal is expected to reach 740,000 short tons and that for nonmetal should reach 13,000,000 short tons by 2000. The rest of the world's demand is expected to experience an average growth rate of 5.4 percent and cumulative demands of 29,000,000 short tons nonmetal and 2,400,000 short tons primary metal by 2000.

Lynd's (1982) conservative estimate of titanium (perovskite) reserves in Colorado (probably using Rose and Shannon's [1960] figures) is the largest of any of the eight states for which estimates were made. The perovskite reserve base of 6,500,000 short tons represents 21 percent of the total 31,000,000-short-ton domestic reserve base for ilmenite and perovskite. Using more recent and accurate information from Buttes' drilling exploration, Thompson (1977) estimated that approximately 100,000,000 short tons of measured ore at a grade of 12 percent TiO_2 contain nearly 12,000,000 short tons of TiO_2 (Table 13). Another indicated 27,000,000 short tons of TiO_2 are indicated to lie within the complex. Adding inferred reserves gives a total reserve estimate of nearly 87,500,000 short tons of TiO_2 within the pyroxenite area of the district. Adding rutile reserves from three states gives a total U.S. reserve base of 33,000,000 short tons, of which Colorado would account for at least 20 percent and probably more realistically about 30 percent.

As seen previously, the Iron Hill alkalic complex represents not only a substantial reserve of titanium but also of columbium, thorium, and rare earths. Most likely the economic development of this unique deposit will depend on coproduct recovery. That most of the country's other titanium reserves lie in the Atlantic Coast region frequently on lands already used for other purposes implies some serious problems and conflicts with future development. The Iron Hill deposit is located almost entirely on public lands and within neither a wilderness nor wilderness study area. Past mining and prospecting, well-established activities in this sparsely populated area, are advantageous to the development of the resource. A major disadvantage is remoteness from a major rail line. The dry titanium concentrates would be trucked 30 miles to Gunnison, thence another 65 miles over 11,300-ft Monarch Pass to the closest rail head, at Salida, thence by rail to a chemical plant.

Table 13. Estimated titanium (ilmenite and perovskite) resources in the Iron Hill complex. Potential resources figure from Rose and Shannon (1960) is minimum tonnage figure. Reserves from Thompson (1977). All figures in short tons.

Potential Resources		Grade
Ore	100,000,000	6.5 % TiO_2, 7 % Fe, 0.1 % V_2O_5
TiO_2	6,500,000	
Fe	11,500,000	
V_2O_5	50,000	

Ore Reserves	Ore	TiO_2	Grade
Measured	97,000,000	11,640,000	12 % TiO_2
Indicated	227,000,000	27,240,000	12 % TiO_2
Inferred	419,000,000	48,604,000	11.6 % TiO_2
Total	743,000,000	87,484,000	

Manganese

Manganese is essential to the U.S. steel industry with no economic substitute available; hence, continued supply is absolutely vital to the defense effort and to the industrial economy. It is essential to iron and steel production because it controls oxygen and sulfur, making the steel workable. Manganese is also used as a deoxidizer in copper alloys, in chemical and battery applications and as an alloying element with several nonferrous metals, chiefly aluminum.

Manganese is a gray-white metal resembling iron, but it is harder and extremely brittle, which makes it valueless as a pure metal. The important valence states of manganese are +2, +4 and +7 to which MnO (manganese oxide), MnO_2 (manganese dioxide), and MnO_4 (permanganate ion) correspond, the latter being used as an antiseptic and in quantitative analyses because of its strong oxidizing power.

Most manganese ores, concentrates, nodules, and sinter for metallurgical purposes usually contain 35 percent or more manganese. The Mn-Fe ratio ideally is about 7.5 to 1 when used to manufacture standard ferromanganese containing 78 percent Mn. Principal manganese ferroalloys are ferromanganese, silicomanganese and ferromanganese-silicon, the choice depending on the carbon and silicon specifications of the steel being made and on conditions during steelmaking.

As one of the more abundant elements in the earth's crust, manganese also is one of the cheapest metallic elements used to alloy with iron. The primary concern regarding supply is the geographic distribution of manganese deposits in relation to the geographic distribution of steel manufacture. The USSR is self-sufficient in manganese, whereas the U.S., Japan, and Western Europe are all manganese deficient. These three countries obtain manganese supplies from six countries, mainly in the Southern Hemisphere, the Republic of South Africa being the most important because it has nearly one-half of the world's ore reserves and exports significant quantities of both ore and ferroalloys. The

USSR, with reserves nearly as great as the Republic of South Africa and together holding about 80 percent of the world's total reserves, no longer furnishes manganese to market economy countries.

The U.S. has no known manganese ore reserves containing 35 percent or more manganese. Although several low-grade and/or refractory deposits are known, the potential for economic extraction or for discovery of commercial land-based deposits is not great. A second major problem is the significant loss of domestic capability to convert ore to ferroalloy which forces the U.S. steel industry to rely on imports. This loss severely limits our ability to protect domestic producers from supply interruptions and makes the U.S. even more dependent on foreign sources of ferromanganese.

Manganese consumption in the U.S. in 1982 fell sharply from that of 1981. Manganese ore consumed fell from 1,076,631 short tons in 1981 to 608,741 short tons in 1982. Of the 562,065 short tons of manganese ferroalloys, 93.3 percent went into the production of various kinds of steel, 3.68 percent into cast irons, 0.062 percent into superalloys (excluding that made from medium- and low-carbon ferromanganese and silicomanganese), 2.12 percent into alloys other than steel and superalloys, and 0.84 percent into miscellaneous and unspecified uses (Jones, 1982). The huge decrease in imports of manganese ore from 1981, about two-thirds, resulted because of the 40-percent decrease in steel production, inventory reduction program by producers, and the relative percentage increase of manganese ferroalloys and metals to ore (nearly four times). Distribution of the 1982 supply was 55 percent from the Republic of South Africa, 19 percent from Gabon, 16 percent from Australia, 4 percent from Morocco, 3 percent from Brazil, 2 percent from Canada and 1 percent from Mexico. Imports of manganese ferroalloys and metal declined but not nearly as much as for ore. The Republic of South Africa remained the leading supplier, providing nearly one-half with France, Mexico and Brazil together supplying about one-third of total ferromanganese imports. Much of the imported ore is converted to ferromanganese, but proportionately, domestic conversion is decreasing while imports are increasing.

U.S. manganese demand is expected to increase at an annual rate of 1.6 percent over that of 1981 to 1,400,000 short tons by the year 2000. World demand, equated to 1981 mine production of 9,500,000 short tons is forecast to rise at a 2.3-percent annual rate to nearly 15,000,000 short tons in 2000. World reserves, estimated at 1 billion short tons are more than four times as great as the 1981-2000 cumulative world demand (Jones, 1983).

Concentrations of manganese have been discovered over wide areas of the ocean floors as oxide nodules and along midocean ridges as oxide crusts. Deposits having an average manganese content of 25 percent, 5 percent iron, 1.4 percent nickel, 1.2 percent copper and 0.2 percent cobalt have been delineated by sampling, photography and seafloor traverses with television cameras. However, recovery of manganese from extensive seabed deposits by U.S. firms is impeded by serious legal and technical problems.

The U.S. Bureau of Mines, as part of its Minerals Availability Program, investigated the availability of manganese from known domestic occurrences (Kilgore and Thomas, 1982). The Sunnyside Mine in San Juan County is one of eight U.S. deposits with significant resources that could be developed in case of an extreme national emergency. The Sunnyside mine has a long history of gold, silver, lead, copper and zinc production from veins formed as a result of the collapse of the San Juan and Silverton calderas. Associated with the veins are large amounts of the manganese silicate mineral, rhodonite, with some rhodochrosite. Kilgore and Thomas (1982) gave a total demonstrated resource tonnage there of 27,898,000 short tons at a grade of 10 percent Mn, containing 2,789,800 short tons of manganese. The manganese occurs in steeply dipping veins and breccia zones up to 60 ft wide. The average dimensions of the deposit are 6,000 ft long, 2,000 ft wide and 15 ft thick with an average depth to mineralization of 160 ft. If manganese production were to be attempted, current precious and base-metal mining would expand to include manganese ore, and old workings would be mined by slabbing or overhand shrinkage stopping. This deposit is generally too refractory to be used as a source of manganese except for the high-silica forms such as ferromanganese-silicon. It is suitable for welding rod coatings and has potential for that purpose.

Other manganese deposits are known in Colorado but most are small and, although locally high grade, are not significant sources of metallurgical manganese. They are mostly epigenetic veins or replacement bodies associated with base and precious metals. In primary or unoxidized deposits the manganese occurs in the gangue usually as rhodochrosite (carbonate), rhodonite (silicate) and manganiferous siderite. Generally the manganese content is too low to be of value.

The Leadville district (Lake County) has the state's largest known deposits of epigenetic manganese with other metals. Nearly one million tons of manganese ore averaging 20 to 25 percent manganese, 25 to 30 percent iron, and 10 to 15 percent silica were produced from about 1890 to 1930, much of which was used in making spiegeleisen. During the same period nearly 3 million tons of Fe-Mn-Ag ore was used as flux in nonferrous smelters where the manganese was lost. The ores occur along the eastern edge of Poverty Flat, on Carbonate Hill, in Iowa Gulch, and on Iron Hill. The Leadville district has about 2 million tons of inferred reserves of unoxidized manganoan siderite containing 10 to 15 percent Mn and 20 percent Fe, and an additional 2 million tons of oxidized ore with slightly higher manganese content (Hedges, 1940).

Ore of similar grade and character occurs in the Red Cliff district (Eagle County) where reserves are estimated at about 1 million tons. Manganese deposits can be seen outcropping about 400 to 500 feet up the canyon wall about 2.5 miles below Red Cliff. The ore occurs in great lenses along the bedding of Carboniferous limestones dipping about 15° northeast. The average content of the ore is approximately 18 percent Mn, 37 percent Fe, and 3 percent Si (Muilenburg, 1919).

In summary, most of the manganese-bearing materials in Colorado are below the 35-percent cutoff for manganese ore. Difficult access, environmental problems, required EISs and permits, high transportation costs to steel plants, and low grade of ore combine to make all the Colorado deposits submarginally subeconomic. These resources would probably not be developed except in the case of an extreme national emergency, in which case their production would be subsidized.

Aluminum - Bauxite

Aluminum, the third most abundant element in the earth's crust, averaging about 8 percent, is a comparatively new metal that has only been produced in commercial quantities for less than 100 years. It is lightweight, about one-third that of steel or copper, has excellent corrosion resistance, is highly malleable and ductile and is easily machined and cast. Its versatility and high strength-to-weight ratio make it ideal for use in military aircraft, missiles, and high-speed surface vehicles and marine vessels. Aluminum oxide is used in making synthetic rubies and sapphires used in construction of lasers and as jewel bearings in precision mechanisms. Refractory-grade calcined bauxite is used as a refractory lining for the furnaces and ladles in the steel, copper, aluminum, and glass industries. All of these uses of the metallic oxide and calcined bauxite exceed that of other metals except iron. All U.S. domestic aluminum production is from bauxite ore, 90 percent of which is imported.

The International Bauxite Association (IBA), formed in 1974 and comprised of 11 member nations, produces 75 percent of the world's bauxite, 48 percent of the alumina production, and has about 62 percent of known resources. Its primary objectives are to raise revenues from its member nations' bauxite-alumina production, maximize benefits through nationalization of the aluminum industry, form collective purchasing agreements, and share information and technology.

The only commercial ore for alumina presently is bauxite. Even though 90 percent of primary aluminum consumed in the U.S. is produced here, only 10 percent of the ore is domestically mined. In addition the percentage of imported alumina (now 30 percent) is steadily increasing because IBA nations want the added value of processing into alumina and the lower shipping costs (about one-half the comparable amount for bauxite). U.S. reliance on imported aluminum raw materials will continue to increase both in quantity and price until technology and processes for utilizing abundant domestic nonbauxitic resources become economically feasible. It is, therefore, imperative that the U.S. investigate and develop technologies for recovering and producing alumina from nonbauxitic resources necessary to provide stable supplies of alumina in the next century. If the U.S. were to face an embargo of bauxite and alumina from foreign sources, nonbauxitic sources would be needed much sooner.

Potential sources of alumina in the U.S. include bauxite (including ferruginous bauxites), clays, alunite, anorthosite, dawsonite contained in oil shale, and coal ash.

The total U.S. bauxite reserve base in 1980 was estimated at 42.6 million short tons containing 17.5 million short tons of recoverable alumina (Baumgardner and McCawley, 1983). From nonbauxitic and ferruginous bauxite an additional 4,608 million short tons of alumina are potentially recoverable at an estimated price of $0.26/lb (1980 price was $0.12/lb).

The lower-cost deposits are, in order, bauxite, ferruginous bauxite, clays, and alunite. Clay deposits, especially in Georgia, account for the major part of the total resource tonnage.

Recovery of alumina from dawsonite in Colorado's Piceance Creek Basin is totally dependent on large-scale development of an oil shale industry. Until such development occurs, dawsonite is only a potential aluminum resource.

Recovery from anorthosite, potentially the largest resource, is not at present technologically feasible; therefore, anorthosite is not considered in the reserve base even though grades average about 27 percent Al_2O_3.

Colorado's potential alumina resources are all nonbauxitic and include kaolinitic clays, alunite, and dawsonite. Kaolin clays (high alumina) occur with lignite beds in the upper 300 to 500 ft of the Denver Formation in the Denver Basin. Individual kaolinite beds 2 to 5 ft thick overlie some lignite beds, and many kaolinitic partings are intimately interbedded with lignite beds. Average analyses of individual beds and partings run 24 percent Al_2O_3 (Kirkham and Ladwig, 1975). Even though the process of recovering alumina from kaolinitic clay is not presently economic as a primary product operation, it may become economically feasible as a by-product of lignite gasification.

Alunite is a potential ore of aluminum in which cell-grade alumina is the primary product with potassium sulfate fertilizer and sulfuric acid as by-products. A large volcanic neck of quartz latite porphyry at Red Mountain, 3 miles south-southwest of Lake City (Hinsdale County) has been pervasively altered by hydrothermal-solfataric processes. The quartz-alunite rock occupies the entire upper portion of the mountain and averages at least 30 percent alunite. The upper portion of Red Mountain, basically above timberline, contains an estimated potential resource of 250 millions tons. Earth Sciences estimates a possible resource of up to 2 billion tons of 35- to 40-percent alunite-bearing rock, which suggests that this deposit may be one of the largest alunite deposits in the world (Hall, 1980).

Other smaller alunite deposits are known in the Rosita Hills Area, Custer County; at Calico Peak near Rico in Dolores County; in the Summitville district in southwestern Rio Grande County; and one at Marble Mountain, 7 miles east of Summitville.

Special problems arise from alunite ores containing phyllosilicate minerals, such as kaolinite, dickite, halloysite, sericite, illite, or pyrophyllite, or an alkali-soluble form of silica, such as opaline cristobalite. Removal of these undesirable minerals creates either increased costs or lower alumina recovery, neither of which are acceptable.

Dawsonite, a sodium aluminum hydroxy carbonate, occurs in portions of the Green River Formation oil shales of the Piceance Creek Basin. The production of even a small portion of the estimated 27 billion tons associated with oil shale is so intimately related to oil shale production that it must be produced either as a by-product or coproduct with oil shale. Therefore, potential dawsonite production is dependent on large-scale oil shale production as well as restricted to areas where dawsonite is actually present in the basin. The greatest thickness, 600 to 800 ft, is in the depositional center of the basin, 17 to 27 miles west of Meeker (Nielsen, 1980). Nielsen (1969) estimated the concentration of dawsonite in these areas at about 12 percent. Careful temperature control (below 550°C) prevents insoluble fluxes with the silica, and the alumina remains in the soluble chi form. Alumina values can then be recovered in a dilute aqueous solution. Significant concentrations of the two important saline minerals, dawsonite and nahcolite, with oil shale are necessary to take advantage of a multiproduct operation. Such concentrations occur in the deeper portions of the basin and hence, a multiproduct operation is not available to many property holders.

However, two major property holders could take advantage of such a multiproduct operation provided they could obtain from the federal government the rights to concurrently mine the saline minerals with the associated oil shale (Farris, 1980).

Vanadium

The strategic importance of vanadium centers on its applications in defense, energy, and transportation. In high-strength low-alloy (HSLA) steels, the addition of only small amounts of vanadium significantly improves ductility, load-bearing strength, grain size, abrasion wear, and shock resistance, and workability, especially in titanium alloys. These properties enable vanadium alloys to be used in aircraft engines and superstructures, turbine rotors, carbides, tool-and-die steels, automotive parts, construction, and other heavy-duty equipment and machinery, especially in high-temperature applications.

In the chemical and processing industries, vanadium finds its principal uses as a catalyst, largely for the manufacture of sulfuric acid and synthetic rubber and intermediate organic compounds, and for sulfurous flue-gas scrubbing. Vanadium also has been used in the manufacture of ceramics and refracoties, container glass, and paint.

The common industrial and stockpile forms of vanadium are ferrovanadium and vanadium pentoxide (Kirk, 1983b). Ferrovanadium is an iron-vanadium alloy containing, at different grades, 38 to 80 percent vanadium, with small variable quantities of carbon, aluminum, silicon, phosphorus, sulfur, and manganese. A third grade specifies 50 to 55 percent vanadium and similar amounts of the other elements. Both stockpile grades of fused-flake pentoxide call for a minimum 98 percent V_2O_5 and very small amounts of phosphorus, sulfur, silica, arsenic, iron, alkalies, and other metallic elements.

The element vanadium was discovered in 1801 by Professor Manuel del Rio at the School of Mines in Mexico City, but he originally named it "erythronium" (Colorado School of Mines Research Foundation, 1961). Four years later the French chemist Collet-Descostils, disputed the discovery, claiming that the element was simply impure chromium, a claim del Rio mistakenly accepted. Erythronium was "rediscovered" in Swedish iron ores in 1830 by Nils Sefstrom, a chemist at the School of Mines in Stockholm. Because of the beautiful colors its compounds formed, Sefstrom renamed the element "vanadium" after Freya Vanadis, the Scandinavian goddess of beauty. Soon after H.E. Roscoe produced the first nearly pure metal in the 1860's, minor uses were found in Europe ink, fabric coloring, leather, glass and pottery, and alloys for armorplate.

About 1900 Professor Arnold of the University of Sheffield in England found that vanadium improved the cutting quality of steel. Commercial production of the metal surged as a result of the use of vanadium steels by early automakers. Henry Ford pioneered their use in his 1908 Model "T" (Morgan, 1980). By 1910 researchers had produced the first ferrovanadium, and ductile vanadium was produced in 1927.

Although figures have not been available in recent years, the leading world vanadium producers are the Republic of South Africa and the USSR, followed by the U.S., China, Finland, Japan, Norway, Chile, and Namibia (Kuck, 1982).

Numerous other countries manufacture ferrovanadium and other alloys (Morgan, 1980). World vanadium production (as contained in ores, concentrates, and slags) from 1977 to 1982 increased from 33,725 short tons to 41,263 short tons (1981). For the same period U.S. production of recoverable vanadium accounted for 11 to 19 percent of world production and fluctuated between 4,098 and 6,504 short tons in response to (1) decline in domestic uranium production, (2) increased material demands by the petroleum industry, and (3) weak overall demand for steel and chemicals (Kuck, 1982, 1983a).

From 1979 to 1982 our net import reliance on vanadium decreased from 43 percent to 24 percent but in 1983 increased to an estimated 52 percent. The principal import sources include the Republic of South Africa, Canada, and Finland. As of 11/30/83, the federal stockpile contained no ferrovanadium and only 1,082,000 lb of pentoxide, compared to goals of 2,000,000 lb and 15,400,000 lb, respectively. In 1983 a GSA contract was awarded to a domestic producer to supply 362,000 lb of Grade A pentoxide.

The importance of Colorado in the history of vanadium production cannot be overemphasized for the State has led all other states in output. From the first recorded production in 1900 through 1906, Colorado was the only commercial source of vanadium and from 1900 to 1931 was essentially the sole domestic source. Through 1945 Colorado has yielded about 34 percent of the world's vanadium. From 1946 through 1968 Colorado accounted for 54 to 85 percent (average 74 percent) of domestic recoverable vanadium, which also amounted to an average 46 percent of the world's recoverable vanadium annually. Table 14 compares Colorado vanadium production since 1900 with that of the U.S. and the world. The figures through 1945 represent the vanadium contained in ores and concentrates, mined, shipped, sold, and received at mills. Figures after 1945 refer to V_2O_5 recovered or recoverable from ores and concentrates, mined, shipped, sold, and received at mills, and so are not exactly comparable to the earlier figures due to milling losses and differences in company reporting procedures.

Because vanadium is a ferrous metal, it is commonly associated with iron ores. With few exceptions, titaniferous iron ore in basic/ultrabasic igneous complexes is the principal sourve of vanadium in countries outside the U.S. Thus the bulk of the rest of the world's vanadium comes from ore in which no specific vanadium minerals are recognizable. Other unusual deposits include uraniferous asphaltites in Peru and Argentina and the oxidized portions of lead-silver veins in South America, Africa, and Spain.

By far most domestic production comes from complex vanadium and uranium-vanadium ores in Mesozoic sedimentary rocks on the Colorado Plateau in Colorado and Utah. Other domestic vanadium sources include vanadium clays in Arkansas, spent catalysts from oil refining and petrochemical plants, imported slags, and vanadium-bearing ferrophosphate, a by-product of phosphate-rock mining and milling operations in Idaho. The U.S. and Japan also are leading producers of vanadium from refinery residues and ashes (Kuck, 1982).

The Colorado Plateau region of western Colorado and eastern Utah has yielded the bulk of all domestic primary vanadium. The most productive area is known as the Uravan Mineral Belt (from "URAnium-VANadium"), which covers westernmost Mesa, Montrose, and San Miguel Counties in Colorado and eastern Grand and San Juan Counties in Utah. The belt is famous for having been the site of the world's first radium and vanadium production, and later the production of uranium for the Manhattan Project during World War II. The region saw its greatest activity as a result of the uranium exploration boom of the 1950s and 1960s.

Table 14. Colorado, U.S., and world vanadium production 1900-1982. Figures in short tons V_2O_5 (1) contained in ores and concentrates, 1900-1945, and (2) recovered or recoverable from ores and concentrates, 1946-1982. Figures for 1961-1982 were originally reported as recoverable or contained vanadium but are tabulated here as equivalent V_2O_5. Data for 1900-1960 adapted from Colorado School of Mines Research Foundation (1961), as compiled from U.S. Geological Survey/U.S. Bureau of Mines Mineral Resources of the U.S. Bureau of Mines Mineral Yearbooks. Data for 1961-1982 compiled from U.S. Volumes and U.S. Bureau of Mines Mineral Yearbooks. W=withheld to avoid disclosing company confidential information; p=preliminary; e=estimated.

	Production				
	Colorado	U.S.	World	% of U.S. Production from Colo.	% of World Production from Colo.
1900	3	3	3	100	100
1901	94	94	94	100	100
1902	114	114	114	100	100
1903	6	6	6	100	100
1904	9	9	9	100	100
1905	0	0	0	-	-
1906	0	0	0	-	-
1907	21	21	25	100	84
1908	0	0	27	-	0
1909	4	4	185	100	2
1910	27	27	251	100	10.7
1911	492	492	1,613	100	30.5
1912	537	537	2,053	100	26.1
1913	773	773	773	100	100
1914	809	809	816	100	99
1915	1,122	1,122	2,706	100	41.5
1916	823	823	2,346	100	35.1
1917	866	866	2,481	100	34.9
1918	455	494	954	92.1	47.7
1919	451	508	1,498	88.8	30.1
1920	943	943	3,229	100	29.2
1921	347	347	744	100	46.6
1922	47	47	187	100	25.1
1923	113	113	811	100	13.9
1924	197	197	1,943	100	10.1
1925	387	387	1,432	100	27.0
1926	555	592	3,457	93.8	16.1
1927	903	903	2,883	100	31.3
1928	824	824	1,810	100	45.5
1929	810	823	3,338	98.4	24.3
1930	810	855	2,811	94.7	28.8
1931	1,130	1,130	2,433	100	46.6
1932	415	483	1,689	85.9	24.6
1933	2	4	112	50	1.8
1934	7	22	242	31.8	2.9

	Production				
	Colorado	U.S.	World	% of U.S. Production from Colo.	% of World Production from Colo.
1935	35	87	906	40.2	3.9
1936	47	124	1,920	37.9	2.4
1937	875	970	3,835	90.2	22.8
1938	1,310	1,441	5,100	90.9	25.7
1939	1,610	1,772	5,727	90.9	28.1
1940	1,784	1,931	2,954	92.4	30
1941	2,245	2,245	5,464	100	41.1
1942	2,741	3,965	7,609	69.1	36
1943	3,713	4,989	8,634	74.4	43
1944	2,729	3,150	5,426	86.6	50.3
1945	2,416	2,653	5,275	91.1	45.8
SUBTOTAL	(33,601)	(37,699)	(98,925)	(89.1)	(34)
1946	720	913	2,543	78.9	28.3
1947	1,121	1,470	3,011	76.3	37.2
1948	687	1,199	2,918	57.3	23.5
1949	1,563	2,127	3,652	73.5	42.8
1950	2,003	2,860	4,305	70	46.5
1951	2,837	3,806	5,908	74.5	48
1952	3,757	4,602	6,781	81.6	55.4
1953	4,053	5,472	7,293	74.1	55.6
1954	4,053	5,417	7,053	74.8	57.5
1955	4,114	5,882	7,282	69.9	56.5
1956	4,996	6,922	7,570	72.2	66
1957	5,607	6,607	7,688	84.9	72.9
1958	4,287	5,424	7,582	79	56.5
1959	5,279	6,657	9,530	79.3	55.4
1960	7,206	8,898	12,495	81	57.7
1961	7,403	9,534	15,563	77.6	47.6
1962	6,677	9,298	14,760	71.8	45.2
1963	5,437	6,891	14,126	78.9	38.5
1964	5,910	7,783	15,297	75.9	38.6
1965	7,167	9,325	17,547	76.9	40.8
1966	6,597	9,218	17,895	71.6	36.9
1967	5,918	8,855	18,318	66.8	32.3
1968	6,231	11,568	23,787	53.9	26.2
1969	W	9,951	33,938	--	--
1970	W	9,491	35,577	--	--
1971	W	9,371	36,582	--	--
1972	W	8,720	36,113	--	--
1973	W	7,810	38,636	--	--
1974	W	8,690	37,046	--	--
1975	W	8,463	50,801	--	--
1973	W	13,161	55,687	--	--
1977	W	11,605	60,176	--	--
1978	W	7,623	63,193	--	--
1979	W	9,849	70,744	--	--
1980	W	8,575	72,284	--	--
1981	W	9,146	73,626p	--	--
1982	W	7,312	38,561e	--	--
SUBTOTAL	(103,623)*	(263,495)	(966,112)		
TOTAL	137,224*	301,194	1,065,037		

*1900-1968 only

world's first radium and vanadium production, and later the production of uranium for the Manhattan Project during World War II. The region saw its greatest activity as a result of the uranium exploration boom of the 1950s and 1960s.

The mineral belt lies in the north-central part of the plateau province in the Paradox Basin fold-and-fault belt, a series of northwest-to-southeast-trending faults and salt anticlines that have deformed a thick section of clastics and evaporites from Pennsylvanian to Cretaceous in age. The principal ore-bearing horizons include the Salt Wash Member of the Morrison Formation and the Entrada and Navajo(?) Sandstones, all of Jurassic age.

In Colorado the belt is a narrow well-defined arcuate band up to several miles wide extending from Gateway in southwestern Mesa County to Egnar in southwestern San Miguel County. Toward the south the belt widens and becomes somewhat less well defined. The belt includes mines that produced more than 20,000 short tons of carnotite ore and most that produced over 10,000 short tons of ore during intensive mining between 1936 and 1943. However, productive deposits lie (1) outside the belt in the Gateway area, along Gypsum Valley, and along the Dolores River east of Egnar, and (2) within the belt's curve north of Paradox Valley and along Gypsum Valley. Fischer and Hilpert (1952) found no definite evidence of the belt's extension westward into Utah (although deposits have been worked there), except possibly for the Polar Mesa area west of Gateway. They also found that uranium-vanadium deposits within the belt tend to cluster in patches of favorable ground up to several thousand feet wide and usually several thousand feet long. Further definition of the belt is based on orientation of these favorably mineralized areas, the long axes of individual deposits within them, and the axes of fossilized logs associated with them--all generally normal or perpendicular to the belt's arcuate trend.

The uranium and vanadium occur in thick (more than 40 ft) lenticular sandstones containing interbedded thin mudstones and mudstone pebble conglomerates within the Salt Wash Member of the Morrison Formation. Favorable sandstone usually is pale to light-yellow brown, speckled with limonite, and characterized by abundant carbonized plant remains. Favorable mudstone beneath ore-bearing sandstone has usually altered to gray, compared to its more normal reddish color. These characteristics generally are useful exploration guides as they indicate the presence of or proximity to ore (Fischer and Hilpert, 1952). The lower portions of the sandstones generally are more favorable sites for vanadium ore, while the upper parts contain the high-grade uranium.

Ore minerals of the Plateau include a number unusual, complex uranium-vandium silicate, phosphates, carbonates, and hydrated oxides and hydroxides. Table 15 lists only those minerals containing solely vanadium or both vanadium and uranium and indicates the primary and minor ore minerals.

The principal secondary uranium-vanadium mineral, carnotite, typically impregnates the sandstone, filling interstices, coating sand grains, replacing plant fragments, and forming what is known as a "roll" or "roll front". Rolls are elongate crescent-shaped bodies generally discordant to bedding, although their long axes lie nearly concordant to bedding. The convex leading edge of the roll marks an interface between oxidized sandstone on the concave side and reduced sandstone on the convex side. One front or interface may extend a long distance and localize several ore bodies.

Table 15. Principal vanadium and vanadium-uranium minerals of the Colorado Plateau. Asterisk indicates principal ore mineral; + indicates minor ore mineral. Compiled from Weeks and Thompson (1954) and Colorado School of Mines Research Foundation (1961).

Types	Name	Chemical Formula/Composition
Oxides:	Alaite	$V_2O_5 \cdot H_2O$
	Doloresite	$3V_2O_4 \cdot 4H_2O$
	Duttonite	$VO(OH)_2$
	Haggite	$V_2O_2(OH)_3$
	Montroseite	$VO(OH)$ or $(V,Fe)O(OH)$
	+Navajoite	$V_2O_5 \cdot 3H_2O$
	+Paramontroseite	VO_2
Vanadates:	Barnesite	$Na_2O \cdot 3V_2O_5 \cdot 3H_2O$
	Brackebuschite	$2(Pb,Mn,Fe)O \cdot V_2O_5 \cdot H_2O$
	Calciovolborthite	$(Cu,Ca)_2(VO_4)(OH)$
	*Carnotite	$K(UO_2)_2(VO_4)_2 \cdot 1\text{-}3H_2O$
	+Corvusite	$V_2O_4 \cdot 6V_2O_5 \cdot nH_2O$
	Delrioite	$CaO \cdot SrO \cdot V_2O_5 \cdot 3H_2O$
	Descloizite	$4(Zn,Cu,Pb)O \cdot V_2O_5 \cdot H_2O$
	Fernandinite	$CaO \cdot V_2O_4 \cdot 5V_2O_5 \cdot 14H_2O$
	+Fervanite	$Fe_4V_4O_{16} \cdot 5H_2O$
	*Hewettite	$CaV_6O_{15} \cdot 9H_2O$
	+Hummerite	$K_2Mg_2V_{10}O_{28} \cdot 16H_2O$
	+Melanovanadite	$2CaO \cdot 2V_2O_4 \cdot 3V_2O_5 \cdot H_2O$ (?)
	Metahewettite	$CaV_6O_{16} \cdot 9H_2O$
	Metarossite	$CaV_2O_6 \cdot 2H_2O$
	Metatyuyamunite	$Ca(UO_2)_2(VO)_4)_2 \cdot 5\text{-}7H_2O$
	+Pascoite	$Ca_2V_6O_{17} \cdot 11H_2O$
	Pintadoite	$2CaO \cdot V_2O_5 \cdot 9H_2O$
	+Rauvite	$CaO \cdot 2UO_3 \cdot 5V_2O_5 \cdot 16H_2O$ (?)
	+Rossite	$CaV_2O_6 \cdot 4H_2O$
	+Sodium vanadate (hewettite analogue)	$Na_2V_6O_{16} \cdot 3H_2O$ (?)
	Steigerite	$Al_2(VO_4)_2 \cdot 6\tfrac{1}{2}H_2O$
	Tangeite	$2CaO \cdot 2CuO \cdot V_2O_5 \cdot H_2O$
	*Tyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot 7\text{-}10\tfrac{1}{2}H_2O$
	Uvanite	$2UO_3 \cdot 3V_2O_5 \cdot 15H_2O$ (?)
	Vanadinite	$Pb_4(VO_4)_3 \cdot PbCl$
	Vanoxite	$2V_2O_4 \cdot V_2O_5 \cdot 8H_2O$
	Volborthite	$Cu_3(VO_4)_2 \cdot 3H_2O$ (?)
Silicates:	*Roscoelite	$(Al,V)_2(AlSi_3)(K,Na)O_{10}(OH,F)_2$
	*Vanadium hydromica	
Phosphate:	Sincosite	$CaV_2O_2(PO_4)_2 \cdot 5H_2O$
Sulfide:	Sulvanite	$3Cu_2S \cdot V_2S_5$
Vanadite:	Simplotite	$CaO \cdot 2V_2O_4 \cdot 5H_2O$

Fischer (1942, 1973) described the vanadium deposits both as roll-type occurrences and as irregular tabular bodies lying essentially parallel to sandstone beds but not following themn in detail. Roscoelite, montroseite, and a vanadium hydromica of undetermined composition are disseminated in the sandstone, filling interstices, coating and replacing sand grains, partly replacing shale pebbles in conglomerate lenses, following bedding planes and conglomerate lenses, and occasionally replacing log and plant material. Thinner, better defined and higher grade ore bodies containing more than 1.5 percent V_2O_5 are separated from one another by barren sandstone. More poorly defined bodies are larger, thicker, and lower grade.

The Jurassic and Triassic deposits rarely contain unoxidized or partly oxidized ore probably because of the shallow depth of the mines. The deeper parts of some mines do reach some unoxidized ore. On the Colorado side of the belt Botinelly and Weeks (1957) classified the uranium-vanadium deposits on the basis of their mineralogy as Group 1, Type 1, high-valent or oxidized ores with the following general mineralogy:

Dominant ore minerals:

Carnotite
Hewettite
Tyuyamunite
Vanadium Clay

Minor ore minerals:

High Valence--	Middle Valence--	Low Valence--
Fervanite	Corvusite	Paramontroseite
Hummerite	Fernandite	Uraninite (with coffinite
Navajoite	Melanovanadite	
Pascoite	Rauvite	
Rossite		
Na vanadate		

Gangue minerals:

Barite
Calcite (rare)
Gypsum
Iron oxide
Pb & Zn carbonates/sulfates

These ores contain high vanadium-uranium ratios--3:1 to 15:1-- in which excess vanadium was present to fix the available uranium in carnotite or tyuyamunite. So, on the basis of actual weight, the ores yield more "red cake" (V_2O_5) than "yellow cake" (U_3O_8), generally at grades of 1 to 5 percent V_2o_5 and up to 1.5 percent U_3o_8.

The origin of the Colorado Plateau uranium-vanadium deposits has been debated for years. The trend of the belt, the orientation of deposits and fossilized logs, the characteristics of the roll fronts, lack of controlling structures, and the wide geographic but narrow stratigraphic extent of the deposits suggest regional sedimentational controls. Shawe (1962) believed that the belt form reflects the toe of a small alluvial fan superposed on a larger fan (head to the southwest) and that formed next to a subsiding basin between the ancestral Unmcompahgre highland to the northeast and an uplift in the Four Corners area. Fluvial sediments deposited during Salt Wash time within and west of the belt represent deflection of the distributary streams from the main fan. The radial orientation of petrified logs indicates that they were rafted by the streams and came to rest oriented parallel to the flow direction. However, Fischer (1942) noted that some logs appeared to have simply fallen over from their place of growth. Following deposition, warm, metal-laden groundwater solutions moved downdip through the permeable sand-filled channels, meeting cooler connate waters in a reducing environment, and establishing an interface along which various ions were precipitated, leaving altered (oxidized) rock behind the interface. Oscillations and downdip movements of the interface account for the concentric layering observed in the ore rolls. Precipitation was induced by the presence of carbonaceous matter, H_2S gas, and transient sulfite derived from the oxidation of preexisting pyrite (Finch and others, 1973; Schwochow, 1978).

A second important vanadium-producing area in western Colorado was worked near Placerville on the San Miguel River in eastern San Miguel County. The Placerville or Lower San Miguel district was first worked for placer gold in the 1870s and for lode base and precious metals from 1890 to 1910. Vanadium ore was mined and milled at Placerville from 1910 to 1920 and again in the late 1940s and 1950s. Cumulative production was about 194,000 short tons of ore at grades of 2.2 to 3.3 percent V_2O_5, yielding about 3.7 million pounds of vanadium and a small amount of uranium.

The productive deposits broadly define a 1.5- to 1.75-mile-wide belt trending generally north-south along Leopard Creek below Alder Creek and curving to the southeast across the river above Placerville and across Fall Creek and Big Bear Creek. Part of a smaller belt lies inside and east of the larger belt and includes the deposits northeast of Saw Pit (Fischer and others, 1947). Permian to Late Cretaceous sedimentary rocks are very slightly warped by several northwest-southeast-trending folds generally reflecting trends of the Paradox Basin fold-and-fault belt to the west. Graben faulting along the same trends has displaced the strata up to 700 ft. A number of small Tertiary laccoliths, stocks, sills, and dikes of varying composition intrude the section (Bush and others, 1959, 1960).

Uraniferous roscoelite and montroseite impregnate the upper Entrada Sandstone as rolls and lenticular masses that define a nearly continuous undulative layer up to 20 ft thick. The layer generally parallels the bedding but does not conform to it in detail. Ore bodies, clustered in poorly defined areas 1,000 to 2,000 ft across, vary from circular to elliptical in plan and usually are convex upward in cross-section, varying from 2 to 20 ft in thickness.

The similarity of these occurrences with those in the Uravan belt suggests deposition under similar hydrologic conditions, but the paleogeographic controls are unknown.

The vanadium-uranium deposits of the Rifle Creek area, 10 miles northeast of Rifle (Garfield County), were discovered about 1909 but were not brought into production until 1923. The mines (mainly the Rifle and Garfield) operated from 1923 to 1932 and were then idle until 1940, after which time they operated intermittently to the early 1950s. Total production amounted to about 25 million pounds of V_2O_5 through 1954 (Fischer, 1960). Both mines produced in the mid 1970s, yielding an estimated 1,160,000 lb V_2O_5 and 56,600 lb U_3O_8, for that period, according Colorado Division of Mines records.

Ores in the Rifle Creek area occur in the massive, cross-bedded Entrada and Navajo(?) Sandstones, which form a 15° to 30° south-dipping hogback off the southwest flank of the White River uplift. The principal minralogy includes roscoelite, a vanadium-bearing mica-montmorillonite or chlorite of undetermined composition, montroseite, tyuyamunite or carnotite, and bayleyite (hydrated magnesium-uranium carbonate). The deposits also are enriched in lead, silver, selenium, and chromium. Vanadium ore minerals fill pore spaces, coat sand grains, and partly replace sand grains.

What the miners originally believed to be three layers or "veins" of ore was interpreted by Fischer (1960) to be actually one layer forming a broad flat "S" shape over a 10,000-ft-long, 80-ft-high interval. The middle limb or "No. 2 Vein" appeared to be a more a series of disconnected small- to moderate-sized ore bodies rather than a continuous mineralized layer. The upper limb or "No. 3 Vein" exposed in the Garfield Mine did not extend far and appeared to have been mostly eroded away by East Rifle Creek.

Fischer (1960) found general similarities between the Rifle Creek and other Plateau deposits in terms of primary and secondary mineralogies and ore occurrences. However, at Rifle Creek, the Navajo and Entrada Sandstones lack the abundant fossil plant debris noted at other Plateau deposits. Although his structural analysis suggested that the deposit lay on the north flank of a shallow basin, he could not offer a more detailed account of the structural and sedimentational controls on ore deposition. The unusual shape of the ore body also poses problems in applying the groundwater-interface mechanism for ore deposition.

In northwestern Colorado vanadium has been produced with uranium from Jurassic sedimentary rocks at two principal localities. The Skull Creek district in southwestern Moffat County lies just north of U.S. Rte. 40, 13 to 22 miles east of Dinosaur. Carnotite, volborthite(?), and copper minerals are associated with clay galls, carbonaceous clay lenses, and carbonized and silicified wood (Nelson-Moore and others, 1978, p. 265-266) in the upper Entrada Sandstone and lower Curtis Member of the Stump Formation.

The Uranium Peak or Coal Creek area, 13 miles northeast of Meeker in Rio Blanco County, has yielded about 854,000 lb of V_2O_5 and over 227,000 lb of U_3O_8 from sparsely distributed deposits in the Morrison Formation (Nelson-Moore and others, 1978, p. 378-381). Carnotite and tyuyamunite occur in a favorable belt less than a mile wide, about 6 miles long, and forming an arcuate pattern around the nose of the anticline (Wright and Everhart, 1960). Other occurrences in this area are reported from sandstone and limestone pebble conglomerate in the Chinle Formation (Triassic).

Minor production of vanadium as a coproduct with uranium was recorded at many other sites in central and western Colorado and from a great age range of clastic rocks (Table 16). A few vein and pegmatite deposits, which usually yield only uranium, reportedly produced small quantities of vanadium.

The last major occurrence of vanadium is in titaniferous magnetite in the alkalic complexes at Powderhorn (described earlier). These deposits figure significantly in the vanadium reserve picture of Colorado, to be discussed below.

Table 16. Minor sources of Colorado vanadium coproduced with uranium. Compiled from Fischer (1968) and Nelson-Moore and others (1978). * indicates deposit in vein or fracture; ** indicates pegmatite deposit.

County	Deposit/Mine Name	Host Formation	Fm. Age	Host-Rock Lithology	U/V Mineral.	Ore Grade % U_3O_8	Ore Grade % V_2O_5
BOULDER	Kekionga-Magnolia	Boulder Creek	p€	gt	ros	--	4.3
	Kipp Lease	Silver Plume	p€	gt	urp	0.54	0.02
CLEAR CREEK	Bonanza	Idaho Springs	p€	sc	pit	0.54	0.03
CONEJOS	Shirley Rae	- -	--	--	---	0.01	0.05
CUSTER	*Beck Mountain	Minturn	ℙ	ss,cg	---	0.10	0.24
	*Floyd Watters	- - -	p€	gn	---	0.11	0.05
DOLORES	Arrow Head	Morrison	J	ss	car-tyu	0.16	2.62
	Barlow	Entrada	T	ss	ros	0.07	1.94
	Black Hat	Morrison	J	ss	ura-cof	0.32	0.65
	Blue Eagle	Morrison	J	ss	car-tyu	0.18	2.36
	Broken Thumb	Morrison	J	ss	car-tyu	0.20	2.48
	Rainy Day	Morrison	J	ss	car-tyu	0.13	3.09
EAGLE	Arrowhead 1	Chinle	T	ss,cg	car	0.22	0.15
FREMONT	Cap Rock	Tallahassee Cr Conglomerate	To	cg	aut	0.11	0.02
	James-Taylor Lease	Echo Park Alluv.	Te	ss	---	0.10	0.12
	Knob Hill	Tallahassee Cr. Conglomerate	To	cg	ura-aut	0.20	0.01
	Misery	Tallahassee Cr. Conglomerate	To	cg	aut	0.17	0.08
	Picnic Tree	Tallahassee Cr. Conglomerate	To	cg	aut-ura?	0.20	--
	Smaller Lease	Echo Park Alluv.	Te	ss	ura	0.30	--
	Sunshine	Tallahassee Cr. Conglomerate	To	cg,va	aut-ura	0.27	--
	Thome	Tallahassee Cr. Conglomerate	To	cg,va	ura	0.27	--
GILPIN	*Carrol	Idaho Springs	p€	gn,pg	pit	0.68	0.02
GRAND	CPJ Claims	Coalmont	Tp	ss,cg	aut	0.35	0.05
HUERFANO	Anal No. 1	Farisita	Te	cg	aut	0.28	0.55
	*Badito Cone	Dakota	K	ss	cof?	0.13	0.009
	Santa Rosa	Sangre de Cristo	P	ss	aut	0.36	1-2
JEFFERSON	Pallaora Lease	Dakota	K	ss	ura	0.20	0.02
LA PLATA	Black Hawk	Cutler	P	ss,cg	---	0.04	0.02
	Lucky Lepracon	Entrada	T	ss	ros	0.24	1.17
	*Shorty	---	T	sy	urp	0.13	0.10
LARIMER	*Copper King	Sherman	p€	gt	pit	0.30	--
	Wahketa Lease	Dakota	K	ss	car	0.07	0.05
MOFFAT	Doc Armor	Wasatch	Te	ss	car-tyu	0.13	0.01
	Lucky Boy	Browns Park	Tm	ss	---	0.20	1.00
	Sugarloaf	Browns Park	Tm	ss	urp	0.15	0.07
	Three Sisters	Browns Park	Tm	ss	urp	0.19	--
MONTEZUMA	Broken Bow	Morrison	J	ss	car-tyu	0.11	1.30

County	Deposit/Mine Name	Host Formation	Fm. Age	Host-Rock Lithology	U/V Mineral.	Ore Grade % U_3O_8	V_2O_5
	CB Claims	Morrison	J	ss	---	0.05	0.10
	Karla Kay	Morrison	J	ss	---	0.08	0.45
	Roberta Jean	Morrison	J	ss	car-tyu	0.17	1.65
	Swallow 1	Morrison	J	ss	car-tyu	0.15	1.45
	Veach	Morrison	J	ss	car-tyu	0.03	0.18
	Virginia Ann	Morrison	J	ss	car-tyu	0.14	1.71
PARK	Amrine & Perrigue	Harding?	O	qtz	---	0.12	0.20
	Garo	Morrison	J	ss	car-tyu-vol	0.93	1.26
	*Gem Dandy	Pikes Peak	p€	gt	aut	0.21	0.01
	Goermer Lease	Minturn	ℙ	ss	aut	0.28	0.59
	*Tedco & MacGeorge	Silver Plume	p€	gt	aut	0.23	--
SAGUACHE	*Beginners Luck	Harding	O	qtz	ura-cof-aut	0.15	0.09
	**Bob Cat	---	p€	gt,pg	---	0.14	0.08
	Bonita	---	Te	--	aut-ura-cor	0.144	--
	La Rue	Morrison & Dakota	J K	ss	aut-tor-urp	0.20	0.11
	Marshall Pass	--	p€	gt	ura-gum	1.06	0.06
	**Ram/Pam Lodes	--	p€	gt,pg	aut	0.06 0.09	0.04 0.09
SAN JUAN	Graysill	Entrada	J	ss	ros	0.05 0.08	1.907 2.41
TELLER	Genevieve	Tallahassee Cr. Conglomerate	To	ss,cg	aut	0.44	0.02

ABBREVIATIONS

Age	
Tm	Miocene
To	Oligocene
Te	Eocene
T	Tertiary
K	Cretaceous
J	Jurassic
Tr	Triassic
P	Permian
ℙ	Pennsylvanian
O	Ordovician
p€	Precambrian

Lithology	
ss	sandstone
cg	conglomerate
qtz	quartzite
gt	granite
pg	pegmatite
sy	syenite
va	volc. ash/tuff
sc	schist
gn	gneiss

Mineralogy	
ros	roscoelite
car	carnotite
tyu	tyuyamunite
aut	autunite
ura	uraninite
urp	uranophane
cof	coffinite
tor	torbernite
vol	volborthite
pit	pitchblende

Kuck (1983b) estimated domestic vanadium demand from 1981 to 2000 to range from 11,000 short tons to 19,000 short tons, representing a probable demand of 14,000 short tons by 2000, or an average annual growth rate of 2.2 percent. Cumulative vanadium demand is expected to reach 282,000 short tons by 2000. Kuck's estimate for probable annual demand of 14,000 short tons was considerably lower than Morgan's (1980) figure of 18,400 short tons because of fundamental structural changes in both the U.S. and world's steel industries. Rising energy costs since 1973 together with the recent recession and import-export imbalances suggest slower growth rates for the ferroalloys industry. The most significant increases in vanadium use are expected in transportation--higher ratios of HSLA to total steel in automobiles and railway cars, vanadium-strengthened railway rails, and titanium-vanadium alloys for aerospace. Vanadifm consumption in construction may increase owing to the growing use of HSLA steels for such permanent structures as bridges and for oil and gas pipelines.

The rest of the world's demand is expected to grow at a higher rate (3.1 percent) than the U.S. because of the growing demand for higher strength steels. Demand for the rest of the world from 1981 to 2000 is forecasted to range from 48,000 short tons to 81,000 short tons, with a probable demand of 60,000 short tons and a cumulative demand of 870,000 short tons by 2000.

U.S. primary demand for vanadium has exceeded domestic production from all resources annually since 1965 (except for 1968). Since 1978 the shortfall has been 50 to 75 percent of production. Comparing Kuck's (1983b) estimated 9,800 short tons of domestic vanadium production by 2000 with the probable demand of 14,000 short tons still equals a shortfall of over 40 percent. Production should increase at nearly the same rate as demand; so, the import-to-demand ratio should remaiin relatively constant. Although this is not the worst case that could arise, the development of domestic vanadium resources still remains vital to domestic industries.

No recent estimates were found for vanadium resources and reserves in the individual productive deposits in Colorado. Kuck (1983b) tabulated only an estimate for "Colorado Plateau," which includes the Uravan Mineral Belt of Colorado, the Zuni Uplift of New Mexico, and Lisbon Valley, Utah. Table 17 shows the significant figures from Kuck's table relative to Colorado. The reserve base for the Colorado Plateau consists of 25,000 short tons of coproduct vanadium contained within uraniferous sandstone and an additional estimated 20,000 short tons of marginal ores. Although vanadium has been recovered from the reprocesing of old uranium-vanadium mill tailings in Colorado, no estimates were given for the remaining vanadium at other Plateau Mill sites. The table shows that the Colorado Plateau deposits account for 13.5 precent of domestic reserves. Perhaps as a result of the region's dominance in past historic production, remaining resources (reserve base) are comparatively not as great. The more substantial reserve base consists of vanadiferous phosphates in Idaho, Wyoming, and Montana, and titaniferous magnetites in Alaska, New York, Wyoming, and Minnesota. The large reserve base for other states is relfected by the Plateau's very small (1.9 percent) share of the domestic reserve base.

These estimates apparently exclude the recoverable potential resources of V_2O_5 in the titaniferous magnetite deposits at Powderhorn, discussed earlier in the section on titanium. Powderhorn contains, in addition to

Table 17. Vanadium reserves of the Colorado Plateau compared to the U.S and rest of the world. Figures in short tons vanadium content (adapted from Kuck, 1983b, Table 5). Reserve base of identified resources includes reserves, marginal preserves, and some subeconomic resources. Data may not add to totals due to independent rounding. Percentages in parentheses represent Colorado Plateau's portion of reserves and reserve base from additional estimated 28,000 short tons vanadium recoverable from titaniferous magnetite deposit at Powderhorn.

	Reserves	% in Colo. Plateau	Reserve Base	% in Colo. Plateau
Colorado Plateau	25,000	--	45,000	--
Total U.S.	185,000	13.5 (25)	2,400,000	1.9 (3)
Total Rest of World	4,630,000	--	15,855,000	--
Total World	4,810,000	0.5	18,000,000	0.25

titanium, columbium, thorium, and iron, an estimated potential resource of 50,000 short tons of V_2O_5, equivalent to about 28,000 short tons of vanadium. Considering the extent of knowledge of the Powderhorn deposits,

increasing the State's reserves by this amount gives a total of 53,000 short tons and a share of total U.S. reserves of about 25 percent. The corresponding increase in the region's reserve base would increase its respective U.S. share to 3 percent.

Even if new uranium-vanadium deposits are discovered in the Uravan Mineral Belt, several problems could significantly hinder expanded future vanadium production in the State. First, most of the vanadium production from the Mineral Belt and from Powderhorn will ncessarily be coproduct production---uranium with the former and titanium and other metals in the latter.

Vanadium production from uraniferous sandstone inherently is tied to the economics of the uranium industry. In the 1980s uranium mine and mill output from the Plateau has been reduced drastically by lower uranium prices resulting from construction delays, cancellations, and health, safety, and disposal problems at some of the country's nuclear generating plants. Consequently, uranium and, therefore, vanadium production from the Plateau will not likely increase until (1) uranium prices improve, and (2) the domestic nuclear generating industry recovers and/or expands, and (3) supply contracts increase to meet foreign demands. It is unlikely that vanadium production would increase from this region solely to meet increased demands by the construction, transportation, or chemical industries.

A second related limitation applies more directly to uranium mining and milling themselves, specifically environmental and health issues of both uranium and vanadium, recent EPA regulations, and technical and economic problems of mill tailing disposal and containment. As of 1982 Colorado had three of the country's 21 vanadium processing facilities--Uravan and Rifle (both operated by Union Carbide) and Canon City (Cotter Corporation), although vanadium recovery at the latter has been discontinued. New regulations for mine and mill drainage and the cost and impacts of moving or in-place treatment of inactive mill tailings could impede future as well as present operations. The role of secondary uranium-vanadium recovery from mill tailings as part of the rehabilitation effort is uncertain.

A third limitation, involving coproduction extraction, applies to the Powderhorn deposits. As noted earlier, recovery of any of the important commodities there will necessitate coproduction of the others. The main difficulty with a major mine and primary treatment or concentrating facility there, besides the current economic situation, is remoteness from rail transport and from a secondary or final treatment site.

Fluorspar

The general term fluorspar can be applied to a substance containing a preponderance of the mineral fluorite, CaF_2. The principal uses for this commodity depend on the different grades mined and milled. Acid-grade fluorspar, containing more than 97 percent CaF_2, is the key component in the manufacture of hydrofluoric acid (HF), the basis for the production of fluorochemical compounds and products. It also is used in such nonfluorinating processes as catalysts and metal-pickling agents. Metallurgical-grade fluorspar, containing less than 97 percent CaF_2, finds its chief use as a flux in aluminum and other metal refining and in steelmaking because it removes impurities, improves slag fluidity, and lowers the melting points of refractory metals. Not included in the federal stockpile is ceramic-grade fluorspar, which is used for the production of specialty glasses, enamels, and fiberglass.

Colorado has produced fluorspar since the early 1870s, but large-scale production did not arise until 1903 when adequate transportation and expanded markets became available. The State can claim a nearly continuous production history from 1880 through 1973, the last year of any production (Table 18). The estimated cumulative total of 1.9 million short tons was valued at $61 million. During the 1950s Colorado's fluorspar mines accounted for nearly 28 percent of the nation's total value. The peak production year of 1972 contributed 31.4 percent (Figure 1). Even the last year of production, 1973, was valued at over $4 million and accounted for over 23 percent of the total U.S. value.

Colorado's principal producing districts and the periods of operation include Jamestown (Boulder County, 1903-1973), Northgate (Jackson County, 1922-1973), Wagon Wheel Gap (Mineral County, 1939-1950), Browns Canyon (Chaffee County, 1927-1949), St. Peters Dome (El Paso County, 1910-1945), and Poncha Springs (Chaffee County, 1934-1954). The Jamestown and Northgate districts accounted for more than 80 percent of the State's production value (Table 19). Small amounts of fluorspar as a primary mineral came from veins in many mountainous areas and as a gangue mineral from metalliferous veins in some of the larger mining districts (Brady, 1975).

Fluorspar deposits in the major districts share the common characteristic of being basically veins, with mineralized breccia fillings and replacements in fault and shear zones. With the exception of Wagon Wheel Gap, all occur in Precambrian igneous and metamorphic rocks, although they may be of different age and origin.

At Jamestown, originally a gold-producing district, fluorspar is believed to have been deposited in breccia zones or reefs zonally arranged around a Tertiary quartz monzonite stock that had intruded Precambrian-age Silver Plume granite and older metamorphic rocks (Goddard, 1946). Veins up to 25 ft wide contain angular fluorspar fragments, coarse- and fine-grained fluorspar, clay minerals, calcite, silica, disseminated pyrite, gold- and silver-bearing base-metal sulfides, and some pitchblende. Due to the high percentages of fine-grained fluorspar and silica, the ore was milled to obtain a commercial-grade product. Veins averaged 60 to 85 percent CaF_2 with breccia zones containing 5 to 60 percent. Crude ore contained 73 to 85 percent CaF_2.

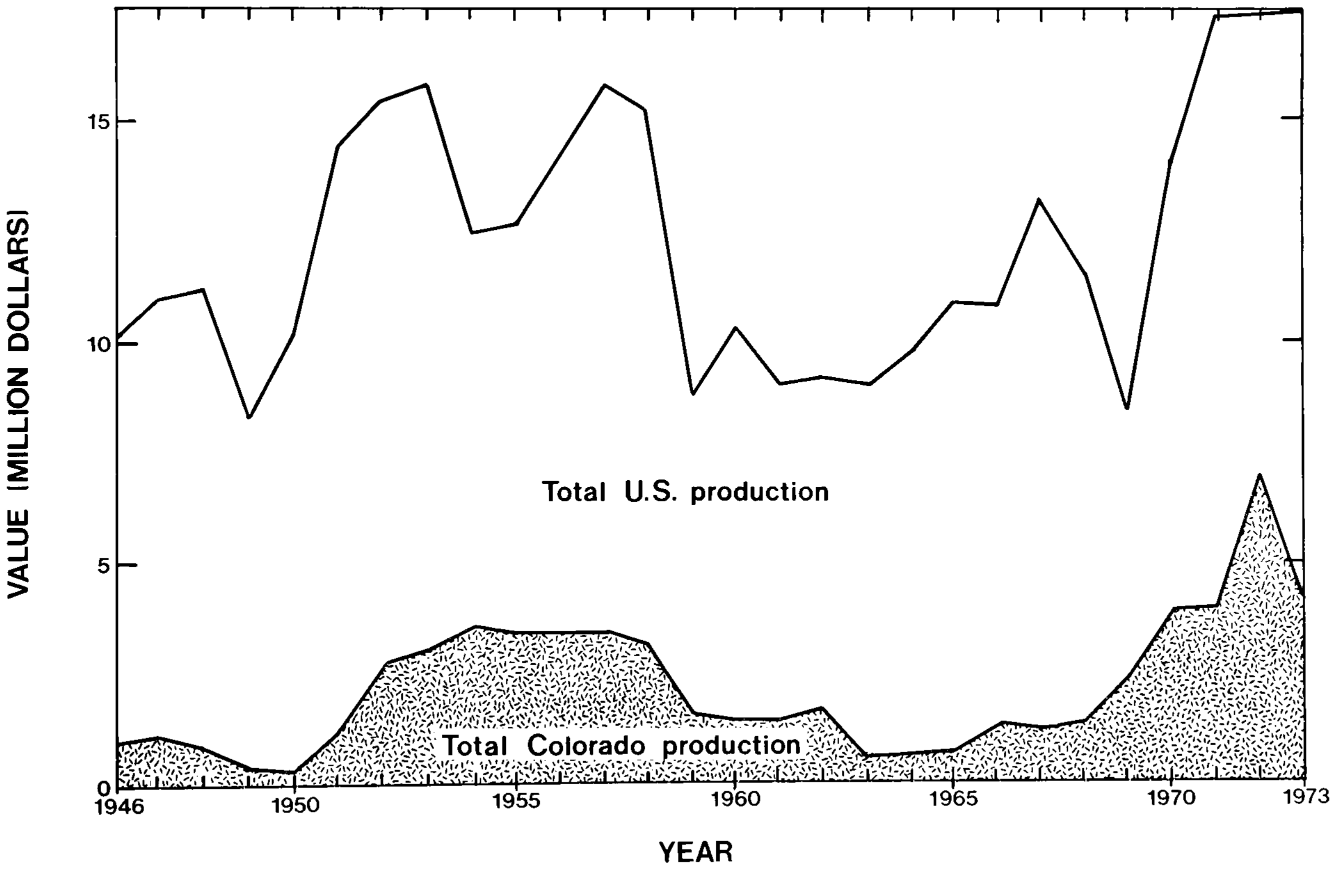

Figure 1. Contribution to total U.S. dollar-value fluorspar production from Colorado for 1946-1973. U.S. Production figures compiled from U.S. Bureau of Mines data (1946-1973). Modified from Brady (1975).

Table 18. Annual fluorspar production in Colorado (from Brady, 1975).

Year	Dollar Value	Production (short tons)	Average value/ton
1880-1909[1]	$ 27,766	5,807	4.78
1910	1,608	268	6.00
1911	4,226	721	5.86
1912	9,834	1,639	6.00
1913	26,592	4,432	6.00
1914	12,992	1,978	6.57
1915	1,482	247	6.00
1916	42,457	8,669	4.90
1917	196,633	17,104	11.50
1918	416,780	38,475	10.83
1919	150,739	9,678	15.58
1920	251,308	12,852	19.55
1921	39,907	3,143	12.70
1922	20,169	2,309	8.73
1923	59,710	6,044	9.88
1924	135,411	12,301	11.01
1925	153,707	11,776	13.05
1926	128,211	10,440	12.28
1927	82,503	6,432	12.83
1928	18,040	1,815	9.94
1929	56,607	4,808	11.77
1930	101,758	9,248	11.00
1931	5,921	529	11.19
1932	3,330	330	10.00
1933	6,778	742	9.13
1934	83,137	6,537	12.72
1935	88,454	6,978	12.68
1936	109,411	9,412	11.62
1937	98,493	7,883	12.49
1938		1,704	
1939	107,459	7,569	14.20
1940	163,285	11,032	14.80
1941	225,069	15,566	14.46
1942	640,938	31,743	20.19
1943	1,164,868	49,145	23.70
1944	1,604,043	65,209	24.60
Year	Dollar value[2]	Production (short tons)	Average value/ton
1945	$ 1,333,735	52,437	25.43
1946	925,867	32,539	28.45
1947	1,066,013	36,050	29.57
1948	0	0	--
1949	394,932	22,324	34.19
1950	289,306	18,489	35.38
1951	215,997	20,661	39.70
1952	1,456,281	29,185	51.60
1953	2,790,146	53,276	53.91
1954	3,027,000	59,197	54.01
1955	3,489,111	--	--
1956	3,340,315	--	--
1957	3,424,600	--	--
1958	3,126,438	--	--
1959	1,432,908	--	--
1960	1,239,444	--	--
1961	1,427,616	--	--
1962	1,619,460	--	--
1963	438,075	--	--
1964	565,740	--	--
1965	630,750	--	--
1966	927,700	--	--
1967	829,230	--	--
1968	1,284,240	--	--
1969	2,272,167	--	--
1970	3,738,645	--	--
1971	3,887,210	--	--
1972	5,435,118	--	--
1973	4,061,117	--	--
Total	$60,938,797	1,900,119[3]	--

[1] 1880-1946 annual production data tabulated by Argall (1949, p. 194)

[2] 1947-1972 total dollar value compiled from Colorado Division of Mines Annual Reports

[3] estimated total production in short tons 1880-1973, excluding 1948, and utilizing fluorspar value data from U.S. Bureau of Mines (1946-1973)

Table 19. Value of annual fluorspar production in Colorado's principal districts, 1947-1973 (from Brady, 1975, as compiled from Colorado Division of Mines Annual Summaries of Mineral Industry Activities in Colorado, 1948-1974).

Year	Boulder (Jamestown)	Chaffee (Browns Canyon)	Jackson (Northgate)	Mineral (Wagon Wheel Gap)
1947	$ 562,013	$ 250,000	--	$254,000
1948	--	--	--	--
1949	181,906	154,000	--	59,026
1950	181,906	--	--	107,400
1951	215,997	--	--	--
1952	528,646	296,901	$ 630,734	--
1953	1,394,580	269,290	1,126,272	--
1954	1,130,000	538,169	1,358,831	--
1955	1,702,290	--	1,786,821	--
1956	1,733,465	--	1,606,850	--
1957	2,070,000	--	1,354,600	--
1958	1,409,102	--	1,717,336	--
1959	1,401,453	--	60,654	--
1960	1,239,444	--	--	--
1961	1,427,616	--	--	--
1962	1,619,460	--	--	--
1963	438,075	--	--	--
1964	565,740	--	--	--
1965	630,750	--	--	--
1966	927,700	--	--	--
1967	829,230	--	--	--
1968	1,277,640	--	6,600	--
1969	862,845	--	1,409,322	--
1970	997,845	--	2,740,800	--
1971	1,064,210	--	2,823,000	--
1972	817,010	--	4,618,108	--
1973	245,259	--	3,815,858	--
Total	$25,454,182	$1,508,360	$25,055,790	$420,426
Percent of total dollar-value production (1947-1973)	48.54	2.88	47.78	0.80

Mines in the Jamestown district generally worked the veins to depths of 50 to 300 ft. The few deeper mines that extended to 500 ft. probably were pursuing the metalliferous ores. Goddard (1946) saw evidence that the veins persisted and perhaps increased in grade below the level of mining at that time. The total vertical range of the deposits reached about 800 ft.

The Jamestown fluorspar genetically is closely associated with the emplacement of the quartz monzonite stock, but rather than an explosive type of origin as was thought at one time, Goddard found that brecciation and layering of fluorspar and country rock in the veins evidently resulted from "mineralization stoping," or collapse and brecciation of the vein material due to dissolution by postfluorspar solutions probably of different chemistry.

Fluorite veins at Northgate in northeastern Jackson County were discovered about 1900 during prospecting for copper. The mineral itself, though, was not identified until 1918, after which the first claims were staked and production began by the early 1920s (Steven, 1960). The fluorspar is localized on bends and deflections along right-lateral strike-slip faults that cut a Precambrian quartz monzonite stock that had intruded an older gneissic complex. The entire sequence was thrust along the Independence Mountain Fault southward over folded Late Paleozoic to Mesozoic sedimentary strata of the North Park Basin.

The commercial fluorspar, probably of late Tertiary age, contains columnar to granular layered masses and aggregates associated with fine-grained quartz and chalcedony and locally disseminated pyrite. Open spaces, encrusted cavities, and large irregular "water courses" indicate that the faults had remained open long enough to allow solutions to circulate freely and slowly deposit silica and fluorite. Even a stalactitic growth of quartz and fluorite was noted on an overhang in a large water course. The Gero-Penber vein, the first of the district's two productive veins, yielded high-grade fluorspar stringers containing more than 80 percent CaF_2. At one mine, a 3- to 6-ft-wide vein averaged 60 percent CaF_2, and an 8- to 11-ft width averaged 40 to 50 percent CaF_2. An approximate 5-ft width across the Fluorine-Camp Creek vein contained 70 to 80 percent CaF_2, and a 16-ft width contained more than 30 percent.

As conspicuously fewer veins occurred at Northgate than Jamestown, the vertical extent of fluorite ore could be seen as a vital economic factor. Steven (1960) determined the known vertical range of ore to be 1,050 ft on the basis of elevations of the surface workings and the bottoms of the deepest mines. Subsequent drilling and exploration by the U.S. Bureau of Mines and some private concerns failed to uniformly confirm minable ore at depth. However, deep exploration in the 1960s and some information in official mine records indicate that production had begun at levels 200 to 300 ft below the previous workings.

From fluid-inclusion studies Steven concluded that the fluorspar was deposited by dilute aqueous mineralizing solutions (predominantly meteoric waters) circulating through open fault spaces in the temperature range of 100^{o} to 150°C.

Fluorspar imports in 1982 amounted to 704,000 short tons (acid- and metallurgical-grade, and fluorspar equivalent from HF and cryolite) compared to domestic production of 77,000 short tons of finished fluorspar (all grades) and 64,000 short tons fluorspar equivalent from phosphate rock. As of 11/30/83, the federal stockpile goals were 1,400,000 short tons of acid-grade and 1,700,000 short tons of metallurgical-grade fluorspar. Total inventories were 895,000 short tons and 295,000 short tons, respectively. The stockpile also contains 899 short tons and 116,863 short tons, respectively, of non-stockpile-grade materials.

Pelham (1983b) estimated the domestic fluorspar demand from 1981 to 2000 to range from 1,100,000 to 1,900,000 short tons annually, representing a probable demand of 1,400,000 short tons/yr by 2000, or an average annual growth rate of 2.3 percent. Probable cumulative demand by 2000 is estimated to be 21,000,000 short tons. The rest of the world is expected to experience a probable average annual growth rate of 3.0 percent. Although domestic fluorspar production fluctuates widely, it is expected to level off at 200,000 short tons annually, which means that increasing amounts must be imported, most likely from Mexico, Africa, and Asia. New domestic resources, lower grade resources, and alternative resources (particularly phosphate rock) must be developed to maintain the current proportion of demand satisfied by domestic production. Since Colorado has none of the characteristic fluorine-bearing phosphate rocks that occur in Florida, North Carolina, Utah, and Idaho, its contribution probably will come from the previously worked districts, namely Northgate and Jamestown. Pelham (1983b) cites USGS estimates allotting Colorado and Utah 34 percent (5,100,000 short tons) of the country's estimated 15,000,000 short tons of minable ore reserves containing 35 percent CaF_2 or equivalent. Of the additional 102,000,000 short tons of subeconomic resources, Colorado holds an estimated 8 percent, or 8,160,000 short tons.

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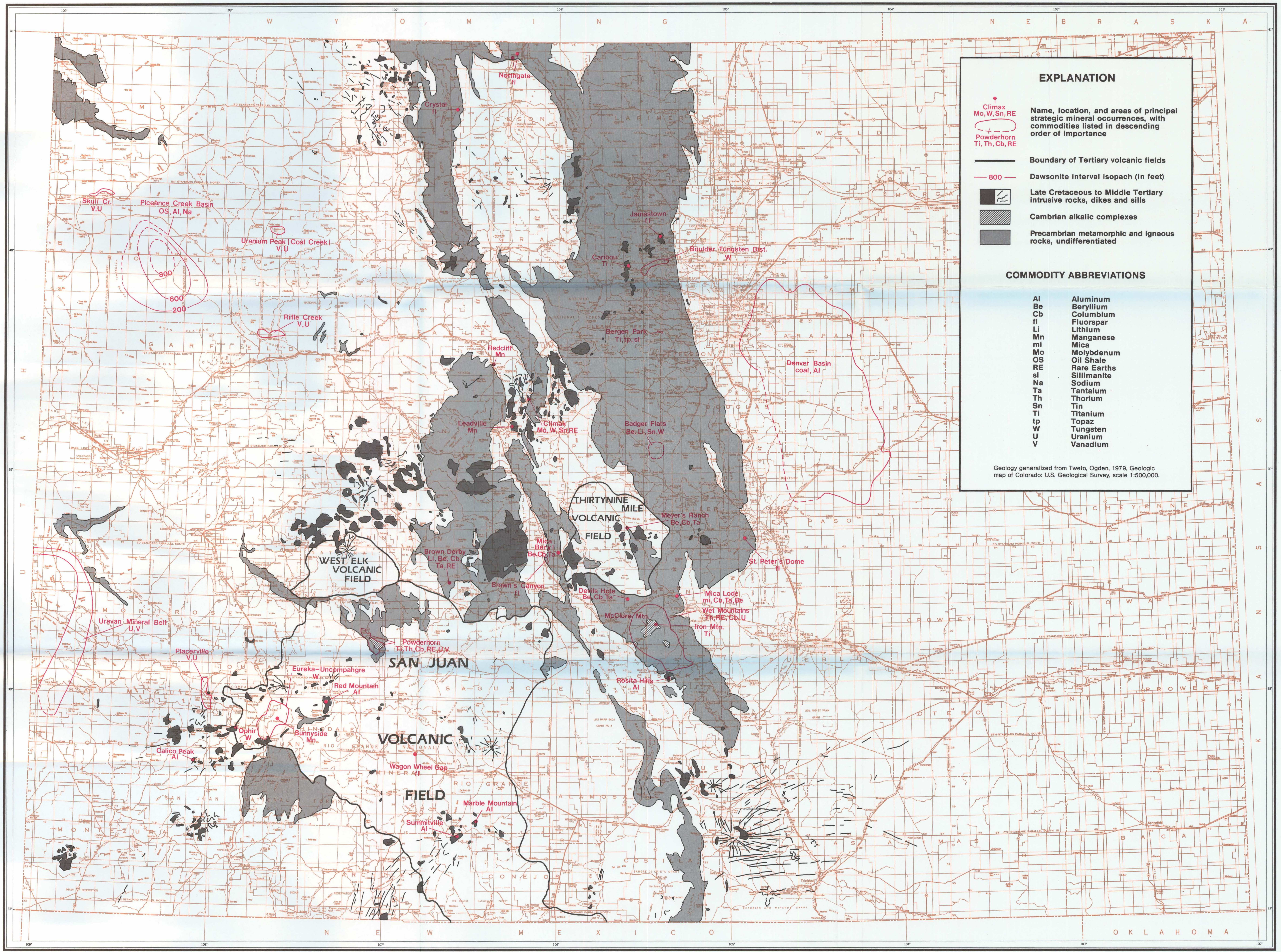
Colorado Geological Survey
Department of Natural Resources
John W. Rold, Director

Principal Strategic Mineral Occurrences in Colorado

By Stephen D. Schwochow and A.L. Hornbaker

Information Series 17
Plate 1
1985



EXPLANATION

Climax Mo, W, Sn, RE / Powderhorn Ti, Th, Cb, RE — Name, location, and areas of principal strategic mineral occurrences, with commodities listed in descending order of importance

— Boundary of Tertiary volcanic fields

— 800 — Dawsonite interval isopach (in feet)

■ Late Cretaceous to Middle Tertiary intrusive rocks, dikes and sills

▨ Cambrian alkalic complexes

■ Precambrian metamorphic and igneous rocks, undifferentiated

COMMODITY ABBREVIATIONS

Al	Aluminum
Be	Beryllium
Cb	Columbium
fl	Fluorspar
Li	Lithium
Mn	Manganese
mi	Mica
Mo	Molybdenum
OS	Oil Shale
RE	Rare Earths
sl	Sillimanite
Na	Sodium
Ta	Tantalum
Th	Thorium
Sn	Tin
Ti	Titanium
tp	Topaz
W	Tungsten
U	Uranium
V	Vanadium

Geology generalized from Tweto, Ogden, 1979, Geologic map of Colorado: U.S. Geological Survey, scale 1:500,000.

Base from U.S. Geological Survey

Scale 1:1,000,000

10 0 10 20 30 40 Miles

10 0 10 20 30 40 50 Kilometers

Lambert conformal conic projection based on standard parallels 33° and 45°

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