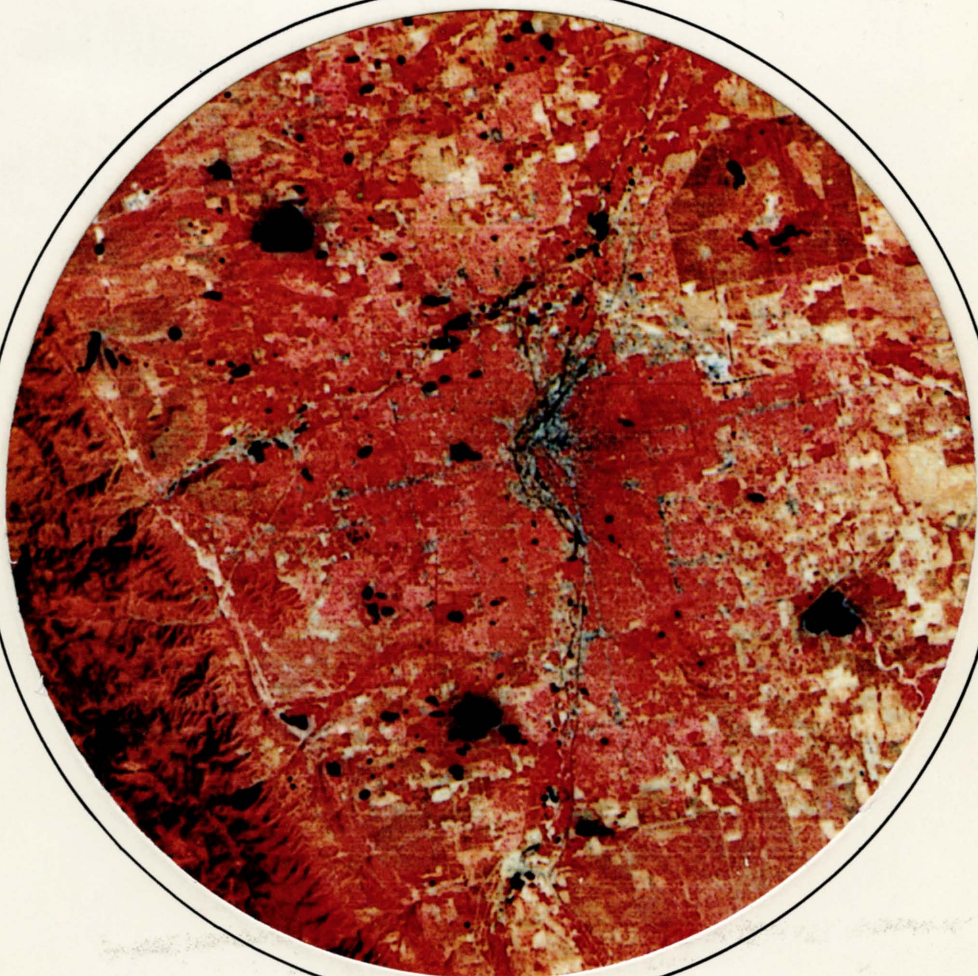
Geology of Denver, Colorado, U.S.A.

Reprinted from BULLETIN OF THE ASSOCIATION OF ENGINEERING GEOLOGISTS
Vol. XIX, No. 3, August 1982

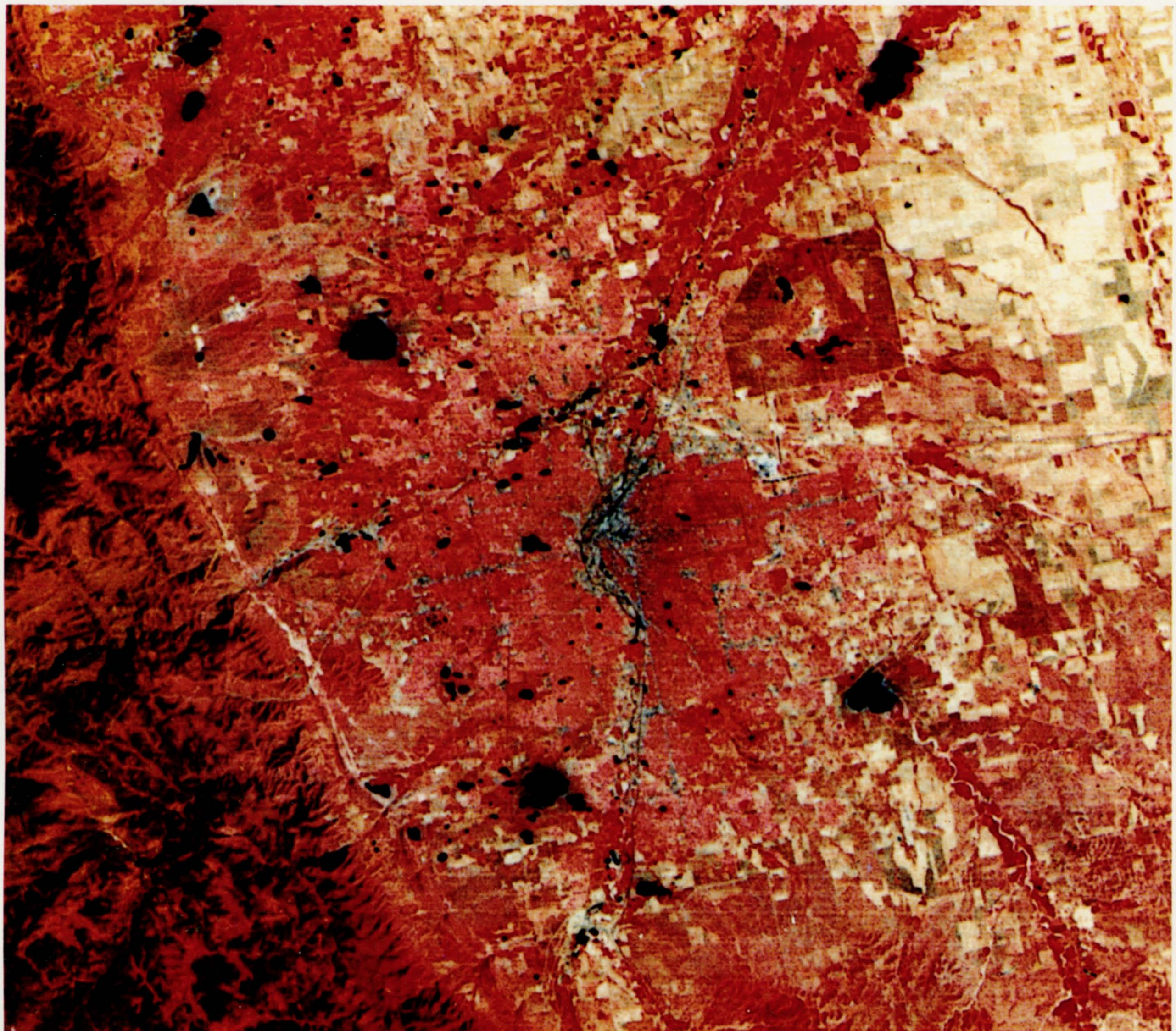
a report of geologic influences on the location, development, and future of the Denver metropolitan area



BY JOHN E. COSTA AND SALLY W. BILODEAU

COLORADO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO / 1982

Geology of Denver, Colorado, United States of America



JOHN E. COSTA AND SALLY W. BILODEAU

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Cover Photo: Landsat false-color composite image (bands 4, 5 and 7) of the city of Denver and surrounding area, August 15, 1973. The image covers the area shown in Figure 1. Denver, the Queen City of the Plains, is in the middle of the image, and the boundary between the Great Plains and Southern Rocky Mountains is clearly seen along the western side of the image.

Bulletin of the
Association of Engineering Geologists
Vol. XIX, No. 3, 1982
pp. 261–314

Geology of Denver, Colorado, United States of America

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FOREWORD

The Executive Council and Board of Directors of the Association are pleased to provide the membership with a new series in the *Bulletin, Geology of The World's Cities*. Cities are the irrevocable focus of all that drives civilization forward; cities are the cauldrons that produce the pressures of cooperation and confrontation between peoples and nations; cities have been the birthplace of culture; cities have been the depletors of natural resources; cities have been the generators of immense quantities of wastes that now peril the environment. Cities, for all of their good and bad, are the fundamental aspect of human life on the planet.

The Association recognizes that each city was originally established for reasons of geologic influence. These same geologic influences are still present, both in the city's shape and structure and as constraints on what can and should be accomplished to prepare the cities for continued service in the coming centuries. In offering this series of papers, the Association hopes to discover elements of geologic influence and impact, so that the whole spectrum of practitioners can better control the renovation and rebirth of cities. By example of this series, peoples of various regions and nations will come to recognize that innovations of others have been applied to overcome some of the stresses on the people and resources of cities. To this end, we recognize the long-time influence of our distinguished Canadian colleague and native Briton, Dr. Robert F. Legget, who has labored in speech, text, and example for more than 45 years to bring this message to us all.

In this premier paper of the series, John E. Costa, an educator, and Sally W. Bilodeau, a practitioner, have presented the Geology of Denver, an American boomtown, grown large and commanding. Its presence, lodged at the eastern edge of the continent's greatest mountain range, marks the real transition from east to west in cosmopolitan America. Denver is the great North American city of our resource-conscious times. The great energies of Denver are people-generated and people-oriented. Denver runs on a 24-hour day, because it is the great sociologic magnet of the continent. Little of its humble frontier beginnings remain for detection by the casual visitor, but its origins are tied to its geologic setting: its development has been controlled by its geology; and its future will be guided by such influences.

Founded in 1858, on the site of placer gold discoveries, Denver has always served as a resource-oriented supply and operations center. Today the city serves a vast area of the central United States as a financial, engineering, scientific, governmental, educational and resource extraction center. The city that was born of resource extraction remains a key element in that activity today.

Denver's very existence, on the fringe of a great mountain range, displays the effect of the natural environment on the development of a city. Its near-region topography varies by nearly 8,000 ft (2,400 m); it lies on a sedimentary basin some 13,000 ft (3,960 m) thick; it consumes ground water and surface water at a phenomenal rate; it demands construction aggregates in alarming quantities; and it produces burdensome quantities of waste. Denver is affected by significant geologic constraints: both collapse-prone and swelling soils, hillslope instability, induced seismicity, flooding, and some areas of rising ground water. Denver is a city of the age and of the decade. The citizens and builders of Denver have learned to respect its geologic setting!

Papers in this series will be the result of cooperation between engineering geologists, geotechnical engineers, hydrogeologists, environmental engineers, seismologists, urban planners, and other allied technical specialists. Most of the papers will be released in the *Bulletin* along with other papers. Occasionally a group of cities in regional areas or nations will be printed in a single *Bulletin* issue. We welcome your continued interest in the series, both as concerned readers and as concerned authors.

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INTRODUCTION

Denver, known as the Mile High City, is the capital of the State of Colorado. The city is located in the west-central United States at latitude 39°44′N and longitude 104°59′W. The city center lies about 12 mi (19 km) east of the southern Rocky Mountains within the broad valley of the South Platte River and within the Colorado Piedmont section of the Great Plains geomorphic province (Figure 1). Denver itself has an area of 115 mi^2 (298 km^2) and a population of about 500,000. However, the Denver metropolitan area has a total population of 1.7 million (including Denver), and sprawls westward into the foothills of the Front Range and eastward onto the Great Plains. The term "Denver metropolitan area" refers to the core city of Denver and its surrounding suburbs, and is represented by the area in Figure 1.

History of Founding

The Denver area was originally occupied by American Indians at least 10,000 to 12,000 years ago. The land was claimed as French territory between 1682 and 1763, as Spanish territory between 1767 and 1800, and as French again between 1800 and 1803. Colorado became part of the Louisiana

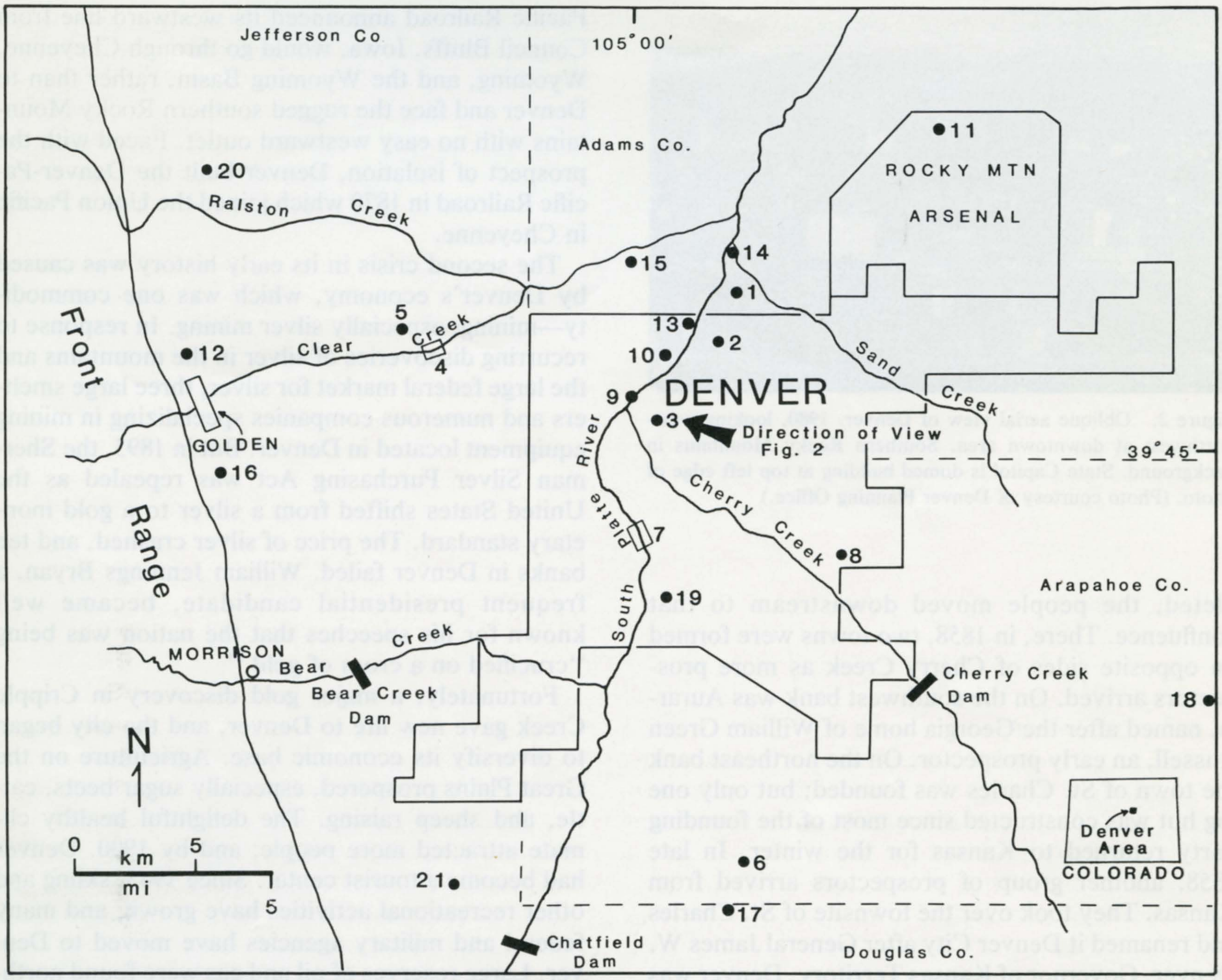


Figure 1. Location map of features in the Denver area discussed in the text. 1. Original site of Montana City; 2. Denver Coliseum; 3. Denver Hilton Hotel; 4. Reach of Clear Creek shown in Figure 13; 5. Ridge Home State School; 6. Isaac Newton Junior High School; 7. Reach of South Platte River shown in Figure 14; 8. Cedar Run Apartments; 9. Gaging station on South Platte River in Denver; 10. Regency Inn, location of strong motion seismograph; 11. Rocky Mountain Arsenal deep-disposal well; 12. Trench excavated across Golden Fault shown in Figure 19; 13. Denver Northside Sewage Treatment Plant; 14. Metropolitan Denver Sewage Disposal District No. 1 Plant; 15. Property Investment landfill; 16. Rooney Road landfill; 17. Arapahoe County landfill; 18. Lowry landfill; 19. Site of the National Radium Institute; 20. Leyden No. 3 Coal Mine used for natural gas storage; 21. Subdivision built over old underground Virginia coal mine. Arrow shows direction of view of photograph in Figure 2.

Territory purchased by Thomas Jefferson from Napoleon Bonaparte in 1803 for $15 million. The land also still belonged to the Arapahoe and Cheyenne Indian tribes, from whom it was eventually purchased in 1861 for $1.25 an acre (Mumey, 1942).

The original site of Denver was near the juncture of Cherry Creek and the South Platte River, where water was plentiful and willows and cottonwood trees offered shade, protection, and game (Figure 1). As early as 1820, it was a favorite camping place for some of the first white travelers through the region, including Colonel John C. Fremont, Kit Carson, and Major Stephen H. Long, and for Indians many years before that.

In the early 1850's, the discovery of placer gold along the South Platte River and its tributaries sparked interest in the area; and in 1858, a group of prospectors from Kansas laid out the first settlement, then called Montana City, on the east bank of the South Platte River about five mi (8 km) upstream from its confluence with Cherry Creek (Figure 1). Later in the year when the gold became de-

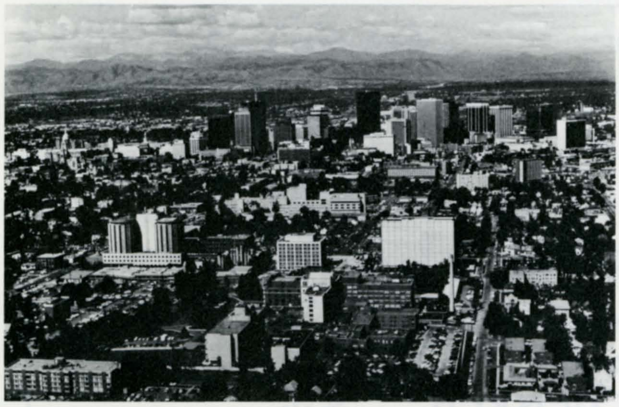


Figure 2. Oblique aerial view of Denver, 1980, looking west-northwest at downtown area. Southern Rocky Mountains in background. State Capitol is domed building at top left edge of photo. (Photo courtesy of Denver Planning Office.)

pleted, the people moved downstream to that confluence. There, in 1858, two towns were formed on opposite sides of Cherry Creek as more prospectors arrived. On the southwest bank was Auraria, named after the Georgia home of William Green Russell, an early prospector. On the northeast bank the town of St. Charles was founded; but only one log hut was constructed since most of the founding party returned to Kansas for the winter. In late 1858, another group of prospectors arrived from Kansas. They took over the townsite of St. Charles and renamed it Denver City after General James W. Denver, Governor of Kansas Territory. Denver was thus founded on a jumped claim. By the spring of 1859, the rival towns of Auraria and Denver had a total population of over 1,000. A year later in April 1860, they merged and adopted the name Denver City.

Placer gold deposits along the South Platte River and its tributaries were soon exhausted, but major discoveries were made in the mountains to the west of Denver. Early Tertiary intrusions 35 to 70 million years old, and rich in gold, silver, zinc, lead, copper, and molybdenum, were the major sources of mineral wealth. Denver grew primarily as a railhead and supply center serving the numerous mining towns in the mountains. The growth of Denver is documented by the rapid rise in population from 5,000 in 1870 to over 35,600 in 1880. Colorado became the 38th state in 1876; and five years later, in 1881, Denver became the state capital.

Denver faced two major crises in its early history. The first crisis occurred in 1866, when the Union Pacific Railroad announced its westward line from Council Bluffs, Iowa, would go through Cheyenne, Wyoming, and the Wyoming Basin, rather than to Denver and face the rugged southern Rocky Mountains with no easy westward outlet. Faced with the prospect of isolation, Denver built the Denver-Pacific Railroad in 1870 which joined the Union Pacific in Cheyenne.

The second crisis in its early history was caused by Denver's economy, which was one commodity—mining, especially silver mining. In response to recurring discoveries of silver in the mountains and the large federal market for silver, three large smelters and numerous companies specializing in mining equipment located in Denver. But in 1893, the Sherman Silver Purchasing Act was repealed as the United States shifted from a silver to a gold monetary standard. The price of silver crashed, and ten banks in Denver failed. William Jennings Bryan, a frequent presidential candidate, became well known for his speeches that the nation was being "crucified on a cross of gold."

Fortunately, a major gold discovery in Cripple Creek gave new life to Denver, and the city began to diversify its economic base. Agriculture on the Great Plains prospered, especially sugar beets, cattle, and sheep raising. The delightful healthy climate attracted more people; and by 1900, Denver had become a tourist center. Since 1945, skiing and other recreational activities have grown; and many federal and military agencies have moved to Denver. Large reserves of oil and gas were found northeast of Denver. Today, Denver is a major industrial, commercial, tourist, recreational, and governmental center in the middle of one of the fastest growing regions in the United States (Figure 2).

Climate

The Denver area is blessed with a semi-arid, temperate-continental climate (Trewartha, 1968) which is strongly influenced by the Rocky Mountains just west of the city. In winter, polar air moving southward is deflected east of the mountain front so that temperatures over the Great Plains can be much colder than temperatures in the mountains a short distance west. The eastward flow of Pacific air masses from the west is disrupted by the Front Range, causing heavy orographic snowfall in the mountains while Denver enjoys sunny skies and dry air. The mountains also block the northward flow of humid Gulf air masses from the southeast. This creates an easterly upslope circulation of air, a condition responsible for Denver's largest snowfalls in winter and heaviest rainfalls in spring and summer.

The mean annual precipitation is 13.8 in. (350 mm), but annual variations range from six inches to 23 in. (152–582 mm). Average annual snowfall is 55 to 59 in. (1,397–1,499 mm). Mean annual evaporation is 50 to 60 in. (1,270–1,524 mm) and the mean annual temperature is 52°F (11°C), ranging from a monthly mean of 70°F (21°C) in July to 28°F (−2°C) in January. Relative humidity averages 48 percent. Clear days (30 percent cloud cover or less) occur 30 to 60 percent of the time, and cloudy days (80 percent or more cloud cover) occur 16 to 36 percent of the time (Hansen et al., 1978).

Geologic Setting

Denver is located near the east front of the Southern Rocky Mountains in the Colorado Piedmont section of the Great Plains, the westward edge of the central stable area of North America. In this section, the Tertiary sedimentary cover that was deposited eastward onto the Great Plains from the erosion of the Rocky Mountains has been eroded by the South Platte and Arkansas River systems, exposing the underlying Cretaceous bedrock (Thornbury, 1965). The topography of the Colorado Piedmont is broadly rolling, with local scarps where resistant bedrock units outcrop. The land slopes from west to east at a gradient of about 10 ft/mi (0.0019 m/m) from 5,300 ft (1,615 m) in Denver to 4,000 ft (1,219 m) at the Kansas boundary.

To the west of Denver lies the Front Range of the Southern Rocky Mountains which extend for 185 mi (298 km) from southern Colorado into Wyoming. The Front Range is a complexly faulted anticlinal arch of primarily Precambrian crystalline rocks reaching elevations of over 14,000 ft (4,267 m) (Boos and Boos, 1957). Where the mountains join the Great Plains, the foothills region consists of steeply dipping Paleozoic and Mesozoic sedimentary rocks forming hogback ridges and gravel-covered pediments. The Golden Fault, a high-angled reverse fault, separates the mountains from the plains (Rocky Mountain Association of Geologists, 1972; Figure 3).

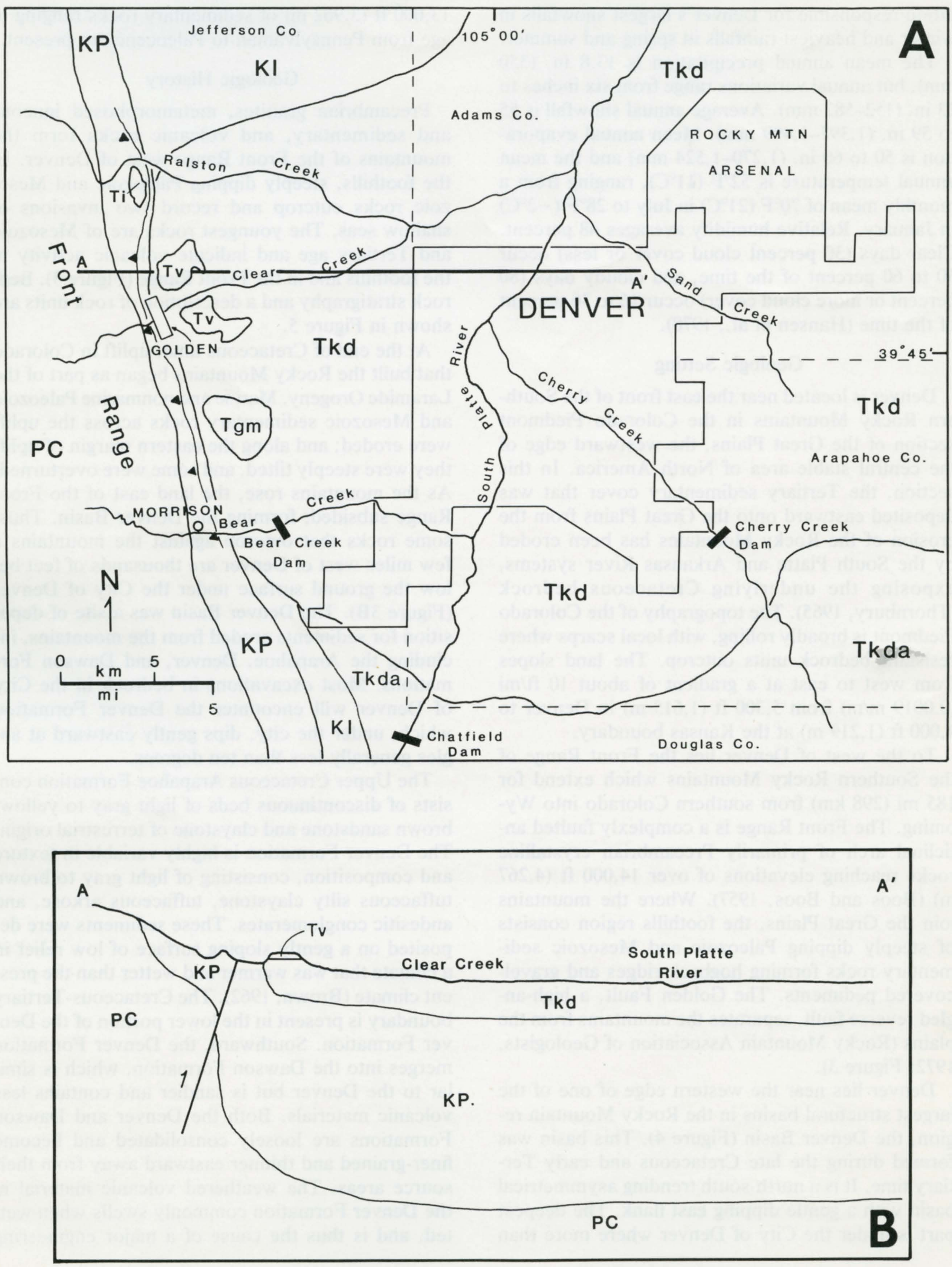
Denver lies near the western edge of one of the largest structural basins in the Rocky Mountain region, the Denver Basin (Figure 4). This basin was formed during the late Cretaceous and early Tertiary time. It is a north-south trending asymmetrical basin with a gentle dipping east flank. The deepest part is under the City of Denver where more than 13,000 ft (3,962 m) of sedimentary rocks ranging in age from Pennsylvanian to Paleocene are present.

Geologic History

Precambrian granites, metamorphosed igneous and sedimentary, and volcanic rocks form the mountains of the Front Range west of Denver. In the foothills, steeply dipping Paleozoic and Mesozoic rocks outcrop and record two invasions of shallow seas. The youngest rocks are of Mesozoic and Tertiary age and indicate volcanic activity in the foothills and in the Front Range (Figure 3). Bedrock stratigraphy and a description of rock units are shown in Figure 5.

At the end of Cretaceous time, uplift in Colorado that built the Rocky Mountains began as part of the Laramide Orogeny. Marine and nonmarine Paleozoic and Mesozoic sedimentary rocks across the uplift were eroded; and along the eastern margin of uplift they were steeply tilted, and some were overturned. As the mountains rose, the land east of the Front Range subsided, forming the Denver Basin. Thus, some rocks that outcrop against the mountains a few miles west of Denver are thousands of feet below the ground surface under the City of Denver (Figure 3B). The Denver Basin was a site of deposition for sediments eroded from the mountains, including the Arapahoe, Denver, and Dawson Formations. Most excavations in bedrock in the City of Denver will encounter the Denver Formation which, under the city, dips gently eastward at angles generally less than ten degrees.

The Upper Cretaceous Arapahoe Formation consists of discontinuous beds of light gray to yellow-brown sandstone and claystone of terrestrial origin. The Denver Formation is highly variable in texture and composition, consisting of light gray to brown tuffaceous silty claystone, tuffaceous arkose, and andesitic conglomerates. These sediments were deposited on a gently sloping surface of low relief in a climate that was warmer and wetter than the present climate (Brown, 1962). The Cretaceous-Tertiary boundary is present in the lower portion of the Denver Formation. Southward, the Denver Formation merges into the Dawson Formation, which is similar to the Denver but is sandier and contains less volcanic materials. Both the Denver and Dawson Formations are loosely consolidated and become finer-grained and thinner eastward away from their source areas. The weathered volcanic material in the Denver Formation commonly swells when wetted, and is thus the cause of a major engineering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problem in the Denver area—swelling soils. North and east of Golden, potassium-rich basaltic flows are interbedded with rocks of the upper Denver Formation, capping North and South Table Mountains. The lavas flowed southeast about 63 to 64 million years ago from old vents now marked by intrusive outcrops northwest of Denver. The flows are about 240 ft (73 m) in total thickness (Van Horn, 1976).

The Green Mountain Conglomerate consists of a conglomerate, sandstone, siltstone, and claystone deposited as basin-fill material by a through-flowing stream draining from the rising Front Range to the west. The formation is found only on Green Mountain, located southwest of Denver, where it is 600 ft (183 m) thick (Scott, 1972a; Figure 3).

Bedrock in the vicinity of Denver was severely eroded prior to the deposition of overlying unconsolidated Quaternary surficial deposits. Analysis of consolidation tests on samples of Denver Formation from downtown Denver indicate 1,000 to 1,400 ft (305–427 m) of Tertiary material once covered the present bedrock (Committee on Denver Subsoils, 1954). The bedrock surface is very irregular. Numerous paleovalleys filled with unconsolidated Quaternary surficial materials underly the city. Alluvial deposits 100 ft (30 m) thick fill an old paleochannel of Cherry Creek, which trends northward from Cherry Creek Reservoir and joins the South Platte River 9.5 mi (15.3 km) north of the present confluence (Hamilton and Owens, 1972b; Shroba, 1980).

Surficial Deposits

In some parts of the Denver area, bedrock appears at the surface and is covered by thin colluvium and residuum formed by in situ weathering. However, most of the bedrock is covered by alluvial and eolian deposits to depths as great as 100 ft (30 m) (Figure 6). In the downtown area, depth to bedrock averages 20 to 40 ft (6–12 m). The surficial geology of the Denver area was first mapped by Hunt (1954) and was the pioneering work on Quaternary stratigraphy in the Denver area. Quaternary

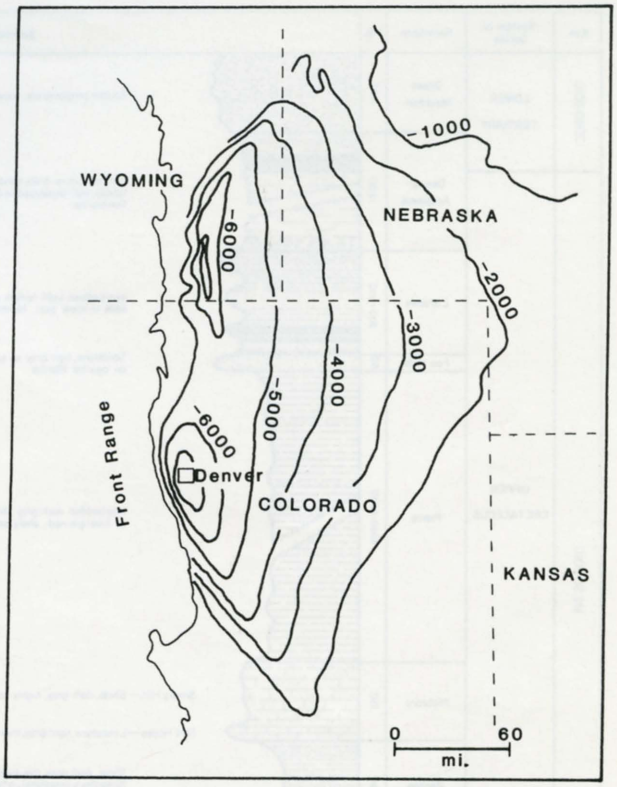

Figure 4. Structure contours on top of Precambrian basement rocks outline the Denver Basin. Contour interval is 1,000 ft (305 m) (from Matuszczak, 1976).

geology and surficial deposits in the Denver area have been further studied by many investigators (e.g., Malde, 1955; Scott, 1960, 1962, 1963; Lindvall, 1978, 1979a, 1979b, 1980; Shroba, 1980; and Van Horn, 1976). Quaternary stratigraphy of the Denver area is shown in Figure 7.

Rocky Flats Alluvium (Scott, 1960) consists of boulders, cobbles, pebbles, and sand in a matrix of locally, red clay. The deposit originated as alluvial fans deposited on pediments by streams draining the Front Range. Thick caliche (pedogenic calcium carbonate) occurs in the upper part of the unit, where it has not been eroded. This alluvium is relatively old—Nebraskan or Aftonian in age (Scott,

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Figure 3. Generalized bedrock geology of the Denver area (A): Map (modified from Emmons et al., 1896; and Trimble and Machette, 1979) Tgm = Green Mountain conglomerate; Ti = intrusive monzonite; Tv = potassium-rich basalt; Kl = Laramie Formation; Tkd = Denver/Arapahoe Formations; Tkda = Dawson/Arapahoe Formations; KP = Pennsylvanian through upper Cretaceous sedimentary rocks; PC = Precambrian cystallines teeth on upthrown side of Golden Fault; A–A′ = Line of cross-section shown in Figure 3B. (B): Schematic cross-section (not to scale) along A–A′ (Modified from King, 1969).

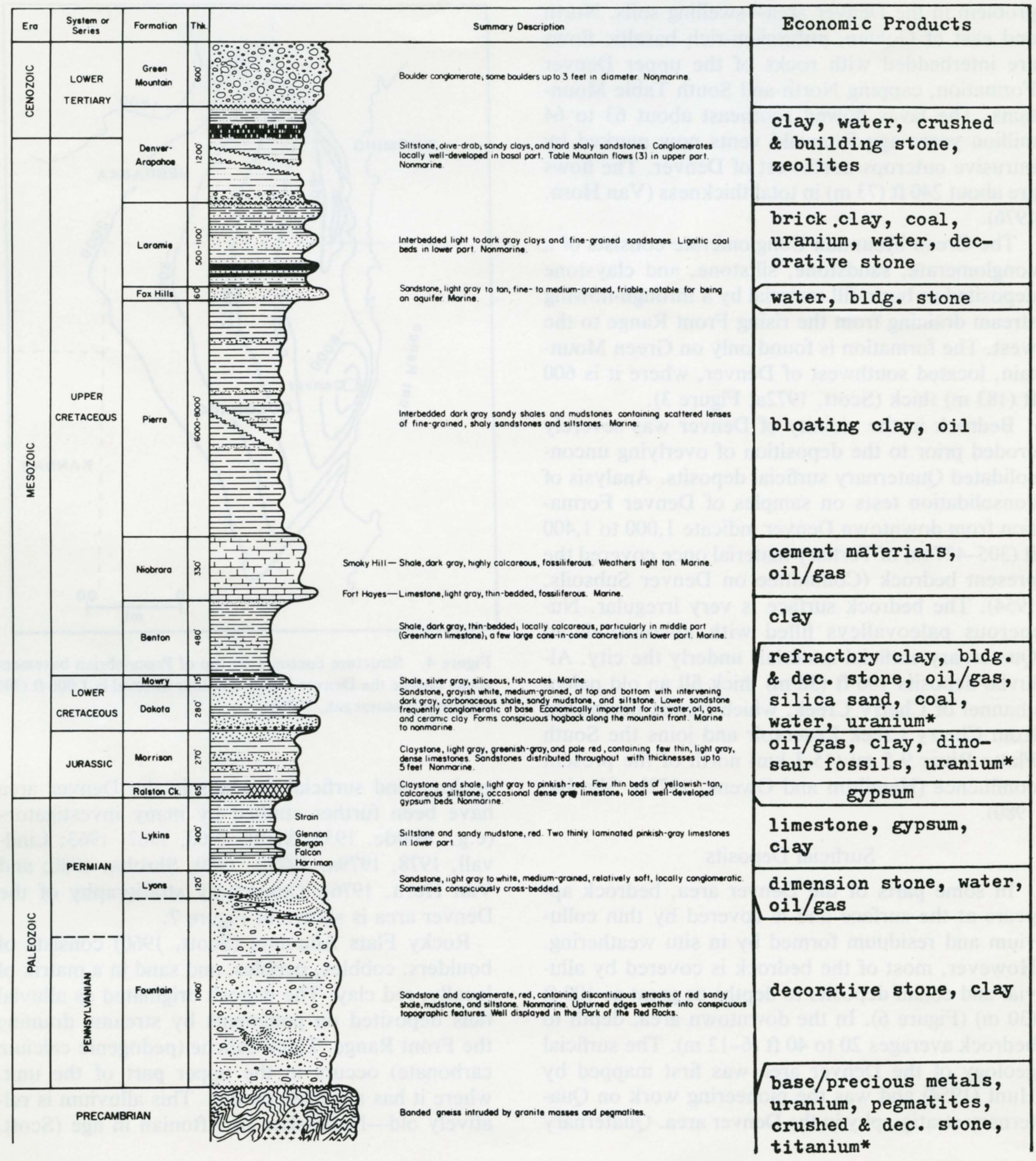


Figure 5. Bedrock stratigraphy, and economic products at Golden, Denver metropolitan area.

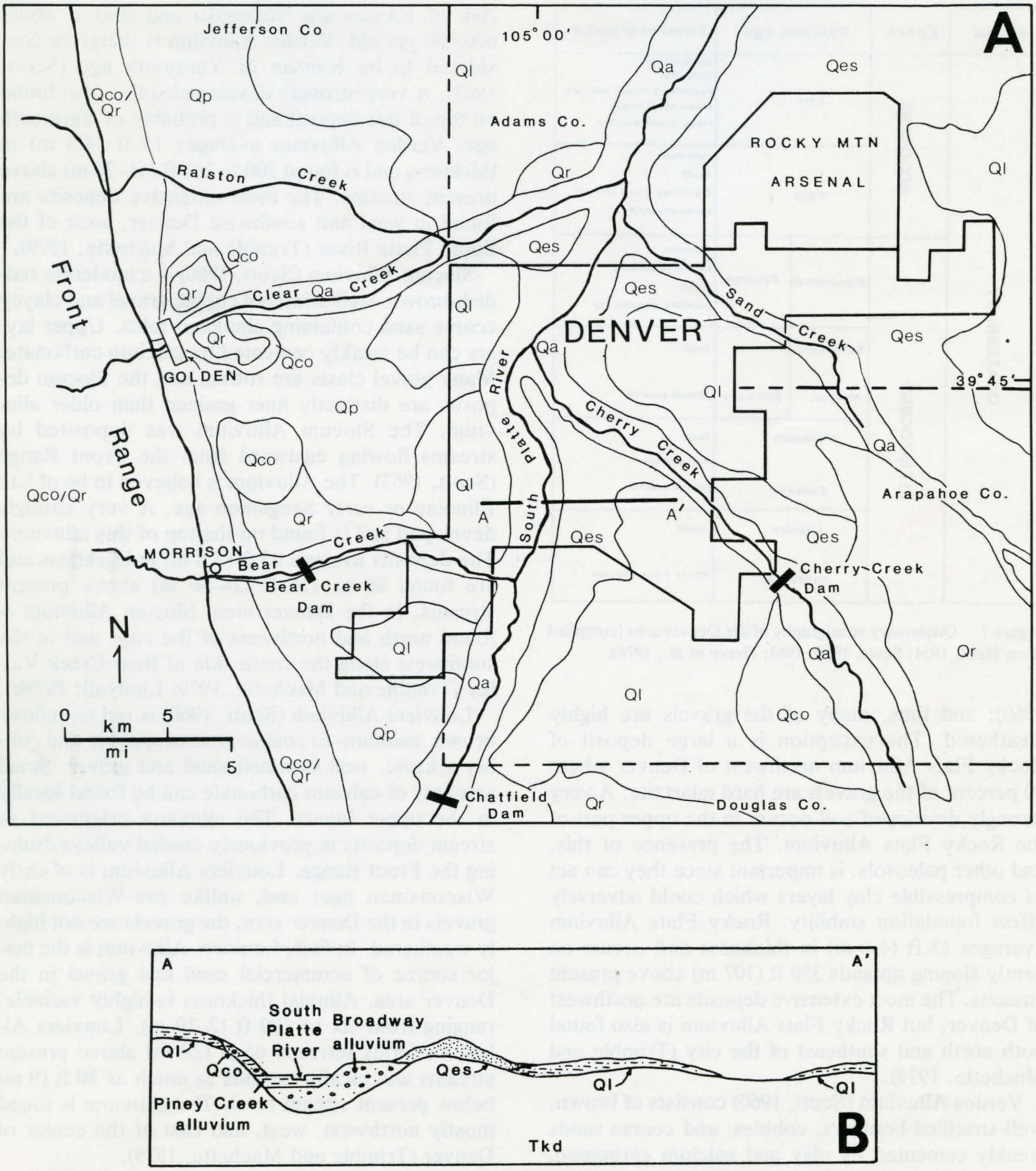


Figure 6. Generalized surficial geology of the Denver area (A): Map (modified from Hunt, 1954; Chase and McConaghy, 1972; and Trimble and Machette, 1979). Qa = alluvium (includes Post-Piney Creek, Piney Creek, Pre-Piney Creek, Broadway, and Louviers Alluviums); Qco = colluvium (includes some landslide deposits); Qes = eolian sand; Ql = loess; Qp = pediment alluvium (includes Slocum, Verdos, and Rocky Flats Alluviums); Qr = residuum (includes bare rock areas). Some deposits may be thin and discontinuous. A–A′ = Line of cross-section shown in Figure 6A. (B): Schematic cross-section of surficial geology (not to scale) along A–A′.

Period	Epoch	Relative age		Formation or deposit
QUATERNARY	HOLOCENE	Late		artificial fill colluvium Post-Piney Creek alluvium eolian sand/loess Piney Creek alluvium
		Early		colluvium (soil) Pre-Piney Creek alluvium eolian sand/loess
	PLEISTOCENE	Wisconsinan	Pinedale	colluvium Broadway alluvium loess Louviers alluvium (?)
		Sangamon		(soil)
		Illinoian	Bull Lake	Slocum alluvium
		Yarmouth		(soil) xxx(ash)xxx
		Kansan		Verdos alluvium
		Aftonian		(soil)
		Nebraskan		Rocky Flats alluvium

Figure 7. Quaternary stratigraphy of the Denver area (compiled from Hunt, 1954; Scott, 1960, 1963; Pierce et al., 1976).

1960); and thus, many of the gravels are highly weathered. The exception is a large deposit of Rocky Flats Alluvium northwest of Denver where 80 percent of the gravels are hard quartzite. A very strongly developed soil occurs in the upper part of the Rocky Flats Alluvium. The presence of this, and other paleosols, is important since they can act as compressible clay layers which could adversely affect foundation stability. Rocky Flats Alluvium averages 15 ft (4.6 m) in thickness and occurs on gently sloping uplands 350 ft (107 m) above present streams. The most extensive deposits are northwest of Denver, but Rocky Flats Alluvium is also found both north and southeast of the city (Trimble and Machette, 1979).

Verdos Alluvium (Scott, 1960) consists of brown, well-stratified boulders, cobbles, and coarse sands weakly cemented by clay and calcium carbonate. Many gravel clasts are weathered and crumble when handled. The alluvium was deposited as terrace fills and as mantles on pediments by streams flowing eastward from the Front Range. A distinctive bed of volcanic ash is found near the base of Verdos Alluvium in about a dozen locations in the Denver area. This ash is equivalent to the Pearlette Ash of Kansas and Nebraska and thus is about 600,000 yrs old. Verdos Alluvium is therefore considered to be Kansan or Yarmouth age (Scott, 1963). A very strongly developed soil is also found on top of this deposit and is probably of Yarmouth age. Verdos Alluvium averages 15 ft (4.6 m) in thickness and is found 200 to 250 ft (61–76 m) above present streams. The most extensive deposits are found in west and southwest Denver, west of the South Platte River (Trimble and Machette, 1979).

Slocum Alluvium (Scott, 1960) is a moderate reddish-brown, well-stratified cobble gravel and clayey coarse sand containing abundant mica. Upper layers can be weakly cemented by calcium carbonate. Many gravel clasts are rotten, and the Slocum deposits are distinctly finer grained than older alluvium. The Slocum Alluvium was deposited by streams flowing eastward from the Front Range (Scott, 1963). The Alluvium is believed to be of late Illinoian or early Sangamon age. A very strongly developed soil is found on the top of this alluvium. The deposits average 25 ft (7.6 m) in thickness and are found 80 to 118 ft (24–36 m) above present streams. In the Denver area, Slocum Alluvium is found north and northwest of the city, and in the southwest along the south side of Bear Creek Valley (Trimble and Machette, 1979; Lindvall, 1979b).

Louviers Alluvium (Scott, 1960) is red to yellow-brown, medium- to coarse-grained, pebbly and cobbly arkosic, well-stratified sand and gravel. Small amounts of calcium carbonate can be found locally in the upper layers. The alluvium originated as stream deposits in previously eroded valleys draining the Front Range. Louviers Alluvium is of early Wisconsinan age; and, unlike pre-Wisconsinan gravels in the Denver area, the gravels are not highly weathered. In fact, Louviers Alluvium is the major source of commercial sand and gravel in the Denver area. Alluvial thickness is highly variable, ranging from six to 100 ft (2–30 m). Louviers Alluvium forms terraces 65 ft (20 m) above present streams and locally extends as much as 30 ft (9 m) below present stream level. The alluvium is found mostly northwest, west, and east of the center of Denver (Trimble and Machette, 1979).

Broadway Alluvium (Hunt, 1954) is reddish-brown, fine- to coarse-grained sand and pebbles. The gravels are generally less than one in. (2.5 cm) in diameter; and thus, the Broadway Alluvium is distinctly finer than Louviers. Broadway Alluvium forms terraces 25 to 40 ft (7.6–12 m) above present streams. In the Denver area, the alluvium forms a pronounced terrace along the east side of the South Platte River through the city. The largest and tallest buildings of downtown Denver are built on the Broadway terrace. Broadway Alluvium is late Wisconsinan (Pinedale) in age and is usually less than 30 ft (9 m) thick.

Loess, consisting of silt with smaller amounts of clay and sand deposited by the wind, is generally found downwind from areas of eolian sand (Figure 6). In south Denver, this boundary lies on the western edge of the University of Denver campus (Hunt, 1954; Shroba, 1980) (Figure 6). Loess is the single most extensive surficial deposit in Denver (Committee on Denver Subsoils, 1954; Trimble and Machette, 1979). Loess and eolian sand underlie an estimated 60 percent of the City of Denver. The loess ranges in age from late Pleistocene to early Holocene.

Eolian sand consists of well-rounded, very fine- to medium-grained sand and sandy silt, derived mainly by wind erosion from both old and young alluvium in stream valleys. It covers most of the uplands east and southeast of the major valleys; but the deposits thin toward the south and southeast. The eolian sand is believed to be early-late Holocene in age (Scott, 1963) and generally extends for one to two mi (1.6–3.2 km) downwind of the source areas.

Pre-Piney Creek Alluvium is light brown to yellow-brown, well-stratified, pebbly silt and sand. It is found 15 to 20 ft (4.6–6 m) above present streams in localized sites along small tributaries in the Denver area. Pre-Piney Creek Alluvium has a moderately strongly developed soil, and deposits have been radiocarbon-dated as approximately 5,500 C-14 yrs old (Scott, 1963).

Piney Creek Alluvium (Hunt, 1954) is common in nearly every valley in the Denver area. It is a brownish gray, humus-rich, well-stratified silt, sand, and clay. Piney Creek Alluvium originated by sheet erosion from local soil-covered slopes and averages 10 ft (3 m) thick. Scott (1963) believes this alluvium to be about 2,800 yrs old, based on Carbon-14 dates.

Post-Piney Creek Alluvium is usually grayish-brown, loose humic gravel, sand, silt, and clay forming the lowest terraces and the modern floodplains. It is derived primarily from Piney Creek Alluvium and is found less than 20 ft (6 m) above present stream levels. Thickness is usually less than 20 ft (6 m). No soil has formed on this alluvium, which has been dated archaeologically and by Carbon-14 methods as approximately 1,500 yrs old (Scott, 1963).

Upper Holocene colluvium is deposited on slopes by gravity and sheetwash. Thickness is usually greater than five ft (1.5 m), and physical properties vary widely depending on source areas. In various places around the Denver area, landslides have occurred in bedrock and surficial materials. These mass movements include slumps, flows, and falls and are most widespread on the slopes of North and South Table Mountains, Green Mountain, and steeply dipping sedimentary formations adjacent to the Front Range.

GEOTECHNICAL CHARACTERISTICS

The geotechnical characteristics of overburden materials and underlying bedrock in the Denver metropolitan area can be influential factors in determining site-specific building plans and appropriate foundation types. Due to the variable nature of the soil and rock present (Tables 1 and 2), several methods for determining in situ foundation conditions have been used. Usually an exploration program is conducted to determine the general geology and stratigraphy of the site. Particular attention is focused on identifying potential geologic constraints and suitable foundation-bearing strata. Fortunately, the geologic environment of the Denver region is generally favorable for development of a major urban area. Most of the geologic constraints present, such as expansive clays and settling soils, lend themselves readily to engineering solutions. Laboratory testing of overburden and bedrock materials is conducted to define the physical characteristics, engineering properties, and shear strength parameters of soil and rock units for input into foundation design. Typical foundations used in Denver include: spread footings, bearing walls on grade, pads with grade beams, belled piers (caissons) with grade beams, and post-tensioned slabs. Nearly all foundations are designed to fit site-specific conditions dictated by the geology and soils.

Overburden Material

Alluvium, colluvium, eolian sand, loess, and residuum overlie bedrock in the Denver metropolitan area (Table 1). The sands, silts, clays, gravels, cobbles, and boulders that make up these engineering soils occur both as well-defined layers and as lenses and pockets. The depth of overburden varies from less than a ft (0.3 m) to over 100 ft (30 m). The elevation of the eroded bedrock surface can change

Table 1. *Engineering characteristics of surficial deposits.*[a]

Deposit	Values	Trask Coeff.	Dry Density (lbs/ft³)	Sp. Gr.	Moisture Content (percent)	Ll	Lp	Ip	Activity	PVC (lbs/ft²)	Unconfined Compressive Strength (lbs/ft²)	Unified Soil Class.
Colluvium	Range	2.9–10.2	90–106	2.65–2.70	7–23	22–69	NP–40	NP–30		0–3,967	—	CH, SM-SC,
	Mean	4.3	99	2.68	15	44	22	22		1,253		SC, SM, CL,
	No. of samples	7	8	6	8	9	9	9	—	8	—	MH
Post-Piney Creek	Range	3.9–7.3	—	—	—	NP–29	NP–18	NP–11	—	—	—	GW, GP, GM,
Alluvium	Mean	5.1	—	—	—	15	9	6	—	—	—	SC, CL
	No. of samples	5	—	—	—	2	2	2	—	—	—	
Piney Creek	Range					33–47	17–23	15–27	—	—	—	CL, SC, GS,
Alluvium	Mean	14.8	—	2.69	—	42	20	22	—	—	—	SM
	No. of samples	1	—	1	—	7	7	7	—	—	—	
Eolian Sand	Range	—	98–113	2.57–2.65	5–22	NP–39	NP–26	NP–23	—	0	626–940	SC, SP, SM,
	Mean	—	105	2.61	12	26	NP	—	—	0	731	ML
	No. of samples		23	2	23	25	25		—	23	3	
Loess	Range	—	83–114	2.57–2.77	6–27	22–64	NP–43	NP–35	—	0–3,550	1,670–15,304	CL, ML-CL,
	Mean	3.4	100	2.67	15	41	23	18	0.5	810	6,473[b]	CH
	No. of samples	1	48	2	48	55	55	55	—	61	26	
Broadway	Range	5.7–20.0	—	—	—	22–47	NP–27	NP–22	—	—	—	SC, CL, SM,
Alluvium	Mean	12.2	—	—	—	33	19	14	—	—	—	SP
	No. of samples	7	—	—	—	9	9	9	—	—	—	
Louviers	Range	1.8–49.0	—	2.65–2.70	—	18–71	NP–38	NP–33	—	400–6,900	—	GW, GP, GM,
Alluvium	Mean	8.9	—	2.68	—	47	29	18	0.7	2,960	—	SC, SW-SM
	No. of samples	12	—	2	—	7	7	7	—	—	—	
Slocum	Range	—	—	—	—	NP-54	NP-28	NP–21	—	900–4,100	—	GW, GP, GM,
Alluvium	Mean	2.6	—	—	—	31	17	14	0.7	2,430	—	SC, SW
	No. of samples	1	—	—	—	6	6	6	—	—	—	
Verdos	Range	—	—	—	—	31–37	22–24	7–15	—	—	—	GP, SC
Alluvium	Mean	5.6	—	—	—	34	21	13	—	—	—	
	No. of samples	1	—	—	—	2	2	2	—	—	—	
Rocky Flats	Range	6.6–>350	—	—	—	33–70	23–33	10–37	—	—	—	GM, GP, GC,
Alluvium	Mean	107.3	—	2.68	—	54	29	25	—	—	—	SC, CH, MH,
	No. of samples	7	—	1	—	5	5	5	—	—	—	CL

[a] Compiled from: Larsen and Brown, 1971; Van Horn, 1968; Maberry and Lindvall, 1974; Committee on Denver Subsoils, 1954; Shroba, 1980.
[b] 100–500 when wet.

dramatically over short distances. Usually within a given building site, the depth to bedrock is fairly uniform, although changes of up to 20 ft (6 m) have been reported. Subsurface conditions are further complicated by the presence of numerous uncompacted man-made fills.

Shear strength characteristics of the various soil units are determined by composition, thickness,

Table 2. *Engineering characteristics of Denver Formation.*[a,b]

Denver Fm.	Values	Sp. Gr.	Ll	Lp	Ip	Activity[c]	(lbs/ft²) PVC	(lbs/ft²) Unconfined Comp. Stg.	(fps) Vp	(fps) Vs	(lbs/ft³) Dry Density	(%) Moisture Content
Sandstone	Range	—	35–74	NP–45	NP–66	—	0–9,900	2,923–972,000	6,400–8,800	2,660–4,900	97–111	4–15
facies	Mean	2.70	60	28	32	1.03	3,600	302,000	7,690	3,640	106	11
	No. of samples	1	8	8	8	—	9	6	3	3	3	3
Claystone	Range	—	41–99	23–59	24–59	—	2,300–19,418	3,341–32,364	—	—	91–114	14–26
facies	Mean	—	66	35	31	0.65	6,318	12,841	—	—	104	20
	No. of samples	—	32	32	32	—	33	38	—	—	18	18

[a] Compiled from: Van Horn, 1968; Maberry and Lindvall, 1974; Committee on Denver Subsoils, 1954; Shroba, 1980.
[b] Fresh to moderately weathered samples.
[c] Plastic index/percent clay.

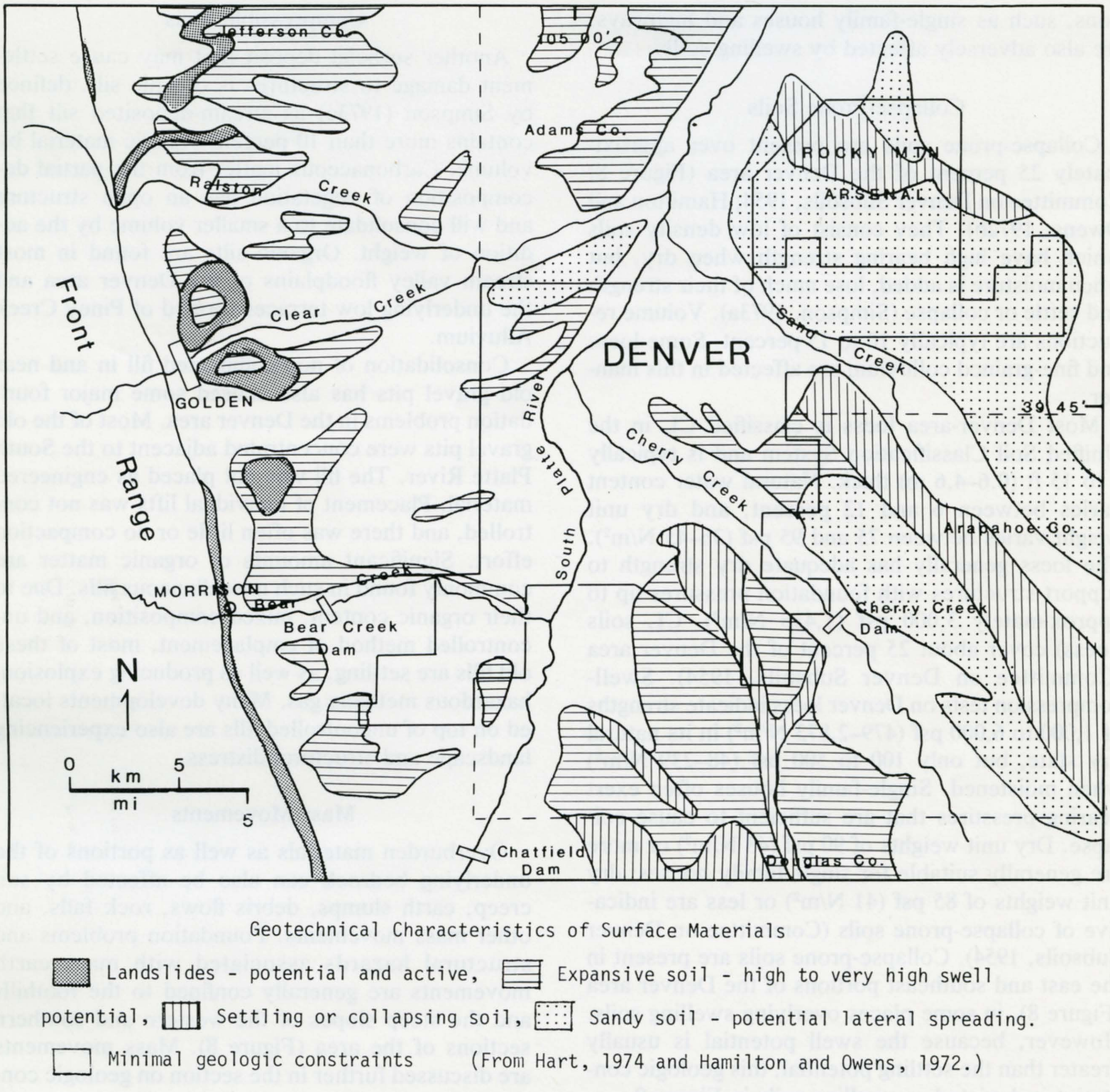


Figure 8. Geotechnical characteristics of surficial material (compiled from Hamilton and Owens, 1972b; Hart, 1974).

density, consolidation and swell properties, and organic content. Related foundation problems can be caused by swelling clays, collapse-prone soils, lateral spreading, subsidence, and mass movements (Figure 8).

Moderately swelling soils are estimated to be present in surficial materials over about 50 percent of the Denver area, particularly in the south, southeast, and western parts as shown in Figure 8. Approximately 25 percent of the area is affected by a high to very high swell potential (Figure 8; Hart, 1974). Swelling soils typically have liquid limits of 45 to 65 percent, and plastic indices of 25 to 35 percent. When tested in a one-dimensional consolidometer, these soils swell 3 to 10 percent under normal loads of 1,000 psf (479 N/m^2), but swelling pressures can be as great as 30,000 psf (14,364 N/m^2) (Hepworth, 1981). Structural damage can occur when swelling is as little as one percent. Lightly loaded structures supported by shallow foundations, such as single-family houses and highways, are also adversely affected by swelling soils.

Collapse-Prone Soils

Collapse-prone soils are present over approximately 25 percent of the Denver area (Figure 8; Committee on Denver Subsoils, 1954; Hamilton and Owens, 1972b). They consist of low density soils which have high bearing strength when dry, but when moisture is added, lose much of their strength and settle or collapse (Simpson, 1973a). Volume reductions are typically 10 to 15 percent. Some loess and fine-grained colluvium are affected in this manner.

Most Denver-area loess is classified CL in the Unified Soil Classification System and is typically 2 to 15 ft (0.6–4.6 m) thick. Natural water content varies between 6 and 12 percent, and dry unit weight varies between 75 and 95 psf (36–45 N/m^2). The loess generally has adequate dry strength to support structures with foundation pressures up to approximately 3,000 psf (1,436 N/m^2). CL soils (loess) cover about 25 percent of the Denver area (Committee on Denver Subsoils, 1954). Swell-compression tests on Denver loess indicate strengths of 1,000 to 6,000 psf (479–2,873 N/m^2) in its natural dry state, but only 100 to 500 psf (48–239 N/m^2) when moistened. Single-family houses often exert bearing pressures that are sufficient to cause collapse. Dry unit weights of 90 psf (43 N/m^2) or more are generally suitable for single-family houses; dry unit weights of 85 psf (41 N/m^2) or less are indicative of collapse-prone soils (Committee on Denver Subsoils, 1954). Collapse-prone soils are present in the east and southeast portions of the Denver area (Figure 8), in some places overlying swelling soils. However, because the swell potential is usually greater than the settling potential, this geologic constraint is depicted as swelling soils in Figure 8.

Lateral Spreading

Lateral spreading is a phenomena by which foundation support can be lost through the horizontal movement of the foundation-bearing materials. Some portions of eolian sand deposits within the Denver metropolitan region can react to foundation loads in this manner (Maberry, 1972b). Typically, sands affected are clean, well-sorted, and dry. Deposits of this nature cover about 20 percent of the area, generally concentrated in the east and northeast portions (Figure 8).

Compressible Soils

Another surficial deposit that may cause settlement damage to structures is organic silt, defined by Simpson (1973c) as stream-deposited silt that contains more than 10 percent organic material by volume. Carbonaceous matter from the partial decomposition of vegetation has an open structure and will consolidate to a smaller volume by the addition of weight. Organic silts are found in most stream valley floodplains of the Denver area and the underlying low terraces formed of Piney Creek Alluvium.

Consolidation of non-compacted fill in and near old gravel pits has also caused some major foundation problems in the Denver area. Most of the old gravel pits were concentrated adjacent to the South Platte River. The fill was not placed as engineered material. Placement of individual lifts was not controlled, and there was often little or no compaction effort. Significant amounts of organic matter are commonly found in such miscellaneous fills. Due to their organic content, mixed composition, and uncontrolled method of emplacement, most of these old fills are settling, as well as producing explosion-hazardous methane gas. Many developments located on top of uncontrolled fills are also experiencing landscape and structural distress.

Mass Movements

Overburden materials as well as portions of the underlying bedrock can also be affected by soil creep, earth slumps, debris flows, rock falls, and other mass movements. Foundation problems and structural hazards associated with mass earth movements are generally confined to the foothills and the steep slopes of the western and southern sections of the area (Figure 8). Mass movements are discussed further in the section on geologic constraints.

Bedrock Units

The Green Mountain Conglomerate has a very limited extent in the Denver area. It is present only at Green Mountain (Figure 3), and is semilithified and flat lying. It varies from easy to difficult to machine-excavate and is moderately erodible. There are active mass movements on the flanks of Green Mountain; and most of the mountain is considered to have a relatively high landslide potential (Hamilton and Owens, 1972b; Scott, 1972b). Foundation problems encountered within the Green Mountain

Conglomerate relate to the heterogeneous composition of the conglomerate and its potential for instability because of steep slopes.

The Denver Formation underlies most of the metropolitan area east of the foothills. The Arapahoe Formation is found north and west of the city, and the Dawson Formation is located to the southwest. The three formations are similar in overall lithology and engineering characteristics, and are, therefore, not differentiated in this discussion but will be referred to collectively as the Denver Formation.

The Denver Formation is composed of layers and lenses of silty claystone, shale, sandstone, and conglomerate. Numerous silty channel sands occur. Some siltstone and claystone beds contain high proportions of montmorillonite and thus exhibit highly expansive characteristics (Table 2). Siltstone and claystone are usually easy to excavate; cemented sandstone and conglomerate require ripping or local blasting. Where exposed, the Denver Formation is moderately resistant to erosion.

Generally, the Denver Formation provides adequate bearing strength for most structures and is the foundation rock for most of the large buildings in the Central Business District (Table 3; Figure 2). Difficulties occur when the Denver Formation lies at such a depth that interception by drilled piers is economically prohibitive. Associated foundation problems include expansivity of some claystone layers located within the zone of seasonal moisture change, or when the construction process induces increased moisture. Some sandstones filling Cretaceous-aged fluvial channels have proven to be compressible. Denver Formation strata, and some surficial deposits, may contain sulfate salts which have corrosive effects on concrete and metal pipes unless special design procedures are used, such as Type II air-entrained cement and cathodically-protected metal pipes (Hart, 1974; Committee on Denver Subsoils, 1954).

West of the City of Denver, older bedrock units are exposed in relatively thin bands paralleling the Front Range (Figure 5). The Laramie Formation and Fox Hills Sandstone are the first formations encountered. They consist of sandstone, siltstone, and claystone. Economic coal beds are present in the Laramie strata. Rock units are moderately well consolidated to hard. Excavation of claystone and siltstone beds is relatively easy; sandstone is moderately difficult. These formations are also moderately resistant to erosion, but some sandstones can be wind deflated if their surface rinds are disturbed. Slope stability is generally good in unsaturated natural material on slopes up to 25 degrees. Coal zones northwest of the Denver metropolitan area have been extensively mined and some subsidence over mined areas has been reported (Amuedo and Ivey, Inc., 1975). The major foundation problem associated with these bedrock formations are potential expansivity of some claystone layers.

The Pierre Shale contains thin beds of montmorillonite and mixed-order clay minerals, thus exhibiting a moderate to very high swell potential. It is over-consolidated, generally easy to excavate at shallow depth, and only moderately erodible. Slope stability is good where the shale is undisturbed, and in cuts less than 45 degrees where ground water is not present.

The Niobrara Formation (including both the Smoky Hill Shale and the Fort Hays Limestone members) has a very thin outcrop along the foothills on the western edge of the Denver area. It is overconsolidated, moderately easy to excavate, and moderately erodible. Slope stability is generally good on natural slopes where ground water is not present, and in materials of moderate to low swell potential. Few foundation problems are associated with Niobrara strata.

The Benton Shale, which is composed of sandstone, shale, and limestone, is overconsolidated, moderately easy to excavate, and moderately erodible. Slope stability is good on natural slopes up to 45 degrees where ground water is not present. Swell potential is low in sandstones and limestone facies, and moderate to very high in shale facies. Foundation problems associated with this formation are generally related to swell potential.

The Dakota Group consists of interbedded sandstone, siltstone, claystone, and conglomerate. The sandstone is generally hard and very resistant to erosion. It forms the resistant edge of the Dakota hogback present along the foothills west of Denver. The claystone member is soft and rapidly erodible by sheetwash. The group as a whole is difficult to excavate and locally requires blasting. Slope stability is good except along dip slopes where there may be local danger of rockslides where resistant sandstone strata are undercut. Foundation suitability is generally excellent except along dip slopes where the rock may slide.

The remaining bedrock formations have only thin outcroppings in the Denver metropolitan area, and will not be discussed here. Engineering characteristics are discussed in Gardner et al. (1971), Simp-

Table 3. *Major engineering structures.*

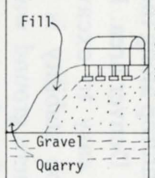
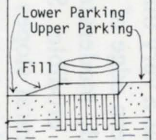
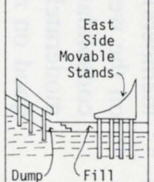
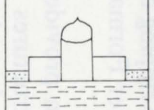
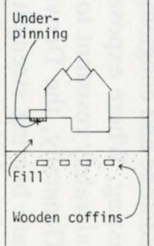
STRUCTURE/ADDRESS	DATE OF CONSTRUCTION	TYPE OF FOUNDATION	GEOLOGIC HOST	PROFILE	COMMENTS	REFERENCE
Denver Coliseum Humboldt Street and Chestnut Place adjacent to I-70	1953	Reinforced concrete pilasters resting on spread footings. Pilasters are 20' long. Footings are 48' long, 7' wide and 6' deep.	Alluvium		This structure is adjacent to a quarry, portions of which have been filled with debris from the stockyards. The building site was moved about 50' east of the quarry to avoid potential settling problems within the fill. A large diameter (2½") drive sampler was developed to test the fill and alluvium.	Peck, 1953.
Denver Sports Arena (McNichols Arena) 17th Avenue and Decatur Street	1974	Caissons-straight shaft 24" to 42" diameter about 20' long 4.0-10.0' into bedrock	Denver Formation		The building is located on sloping terrain. It is partially buried by a planted and landscaped fill which separates the two parking lots.	Plans at City Engineers Office
Mile High Stadium 20th Avenue and Clay Street adjacent to I-25	1948 through 1978	Caissons-straight shaft. 24"-36" diameter; 10-15' into bedrock east side; 5-10' into bedrock west side, (it was critical to keep the east side level due to the movable stands)	Denver Formation		The stadium was originally constructed over the city dump. Portions of the dump have been removed and replaced with engineered fill. The movable stands are the largest structure ever to be moved using water bearings, no settlement has been detected so far.	Plans at Engineers Office, and oral communication with Jim Toole - DMJM, Inc.
Capitol Building Colfax Avenue and Sherman Street	1894	Footing Walls	Denver Formation?		The capitol building is 3 stories high and has one basement. The top of the dome is 272' feet from the ground. This structure was constructed as 3 separate units, the central portion and 2 wings. Each unit was designed to stand independently in case of a partial collapse due to an earthquake. Subsurface access tunnels lead from the capitol building to the adjacent state buildings although they are not used today.	Colorado Dept. of Education Capitol Building pamphlet, and communication with Gretchen Haskins.
Botanical House York Street and 9th Avenue	Around 1900?	Footings	Fill over Alluvium		This historical building began to subside and experience distress. Subsurface investigation revealed an old cemetery under about 20' of fill. The old wooden coffins were collapsing. Several of the gutter downspouts were also discharging water adjacent to the foundation. The downspouts were repaired and the front of the house was underpinned to prevent further distress.	Oral communication with Fu Hua Chen - Chen & Associates, and oral communication with Dr. William Gambill, Botanical House

Table 3. *(continued)*.

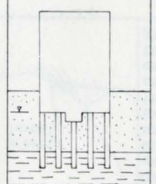
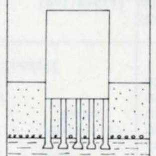
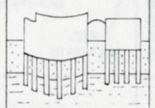
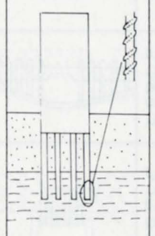
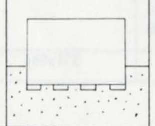
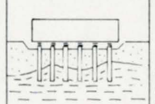
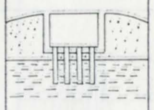
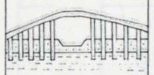
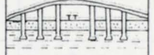
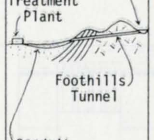
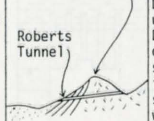
STRUCTURE/ADDRESS	DATE OF CONSTRUCTION	TYPE OF FOUNDATION	GEOLOGIC HOST	PROFILE	COMMENTS	REFERENCE
Police Administration Building 13th Avenue and Cherokee Street	1974	Caissons-straight shaft 70-80' long about 24" diameter 4' to 9' into bedrock (about 60' of alluvium)	Denver Formation		7 story bldg. with 2 sublevels for parking. Lower sections are intermittently dewatered. The lower levels were designed for flooding in the event of a flood on Cherry Creek. The building excavation was made using driven soldier piles and tie backs.	Plans at City Engineers Office and oral communication with Dick Hepworth, Chen and Associates
Lincoln Tower Lincoln Street and 18th Avenue	1961?	Caissons-belled about 70' long about 2.0' into bedrock (about 68 feet of alluvium)	Denver Formation		This building is 13 stories tall with a 2 story subsurface parking garage. Immediately above bedrock a gravel layer was encountered which made drilling the caissons very difficult.	Oral communication: Bob Heister-Architect
Symphony Hall (Boettcher Hall) Curtis Street and 14th Street	1974 to 1979	Caissons-straight shaft 24" to 48" diameter 2' to 9' into bedrock (about 40' of alluvium)	Denver Formation		The hall and the arcade are supported on caissons. The adjacent building is an auditorium which is supported on old timber piles.	Plans at City Engineers Office and oral communication with Dick Hepworth, Chen and Associates
First National Bank 17th Street and Welton Street	1957	Caissons - straight shaft with grooved design 5'6" diameter 15' minimum penetration into bedrock (about 50' of alluvium)	Denver Formation		The First National Bank is a 28 story building with 1 sublevel. This grooved design was common practice around Denver in the 50's and 60's when the drill hole exhibited a very smooth wall. An oversized tooth was attached to the drill bit and used to roughen the wall. It was later discovered the method didn't greatly increase the friction bearing capacity so it has been generally discontinued.	Oral communication and plan inspection with James Tolle, DMJM, Inc.
Denver Public Library 13th Avenue and Acoma Street	1954	Pads 4' x 4' to 8' x 8' ave. 7' x 7' thickness from 1'6" to 2'4"	Broadway Alluvium		The library is a 4 story building with 2 sublevels.	Plans at City Engineers Office
Isaac Newton Junior High School Arapahoe Road and Colorado Boulevard	1962	Caissons - straight shaft 30" diameter 4.0' minimum penetration into bedrock (bedrock is 4-23' below ground surface)	Denver Formation		The caissons heaved due to pressure from expansive soils. They were cut down, the school was releveled and shimmed upon the cut caissons. The cost of the repairs was approximately equal to the original cost of construction.	Oral communication with Fu Hua Chen - Chen and Associates. Also in Chen, 1975.

Table 3. *(continued)*.

STRUCTURE/ADDRESS	DATE OF CONSTRUCTION	TYPE OF FOUNDATION	GEOLOGIC HOST	PROFILE	COMMENTS	REFERENCE
Hillcrest Reservoir Happy Canyon Road and Oxford Avenue	1957	Caissons - straight shaft about 18" in diameter about 22' long about 15' bedrock penetration	Denver Formation		The reservoir began to lose water. Swelling soils apparently caused distress in the joints and seams of the reservoir. Excavating around each pier to reduce the skin friction solved the problem.	Oral communication with Fu Hua Chen - Chen & Associates
15th Street Bridge over the Platte River	1975	Piles 30' long with 8-10' of penetration into bedrock	Denver Formation		The piles could not be driven into the shale bedrock so a hole was first drilled, then the piles were driven in.	Plans at City Engineers Office. Oral communication with Mike Minhos
West Evans Viaduct over Santa Fe RR Tracks	1971	Caissons-belled about 2½" in diameter with 6' minimum penetration into bedrock	Denver Formation			Plans at City Engineers Office. Oral communication with Mike Minhos
Foothills Tunnel	Scheduled for 1982		Greenhorn Limestone Dakota Limestone Fountain Formation Precambrian Metamorphics		Scheduled for completion in 1982. The 3.4 mile tunnel will initially bring 125 million gallons of water per day to the Denver Metropolitan area. The tunnel is capable of conducting 500 millions gallons per day. When used to capacity this will double Denver's existing water supply.	Oral communication with Quentin Hornbeck, geologist, Denver Water Board
Roberts Tunnel	1960		Dakota Formation Benton Shale Niobera Formation Entrada Sandstone Pierre Shale Montazuma Shale Precambrian Metamorphics		Roberts Tunnel is 23.3 miles long and diverts western slope water to Denver by taking water under the Continental Divide. Presently it is operating at 300 to 400 second feet of water but its capacity is 1000 second feet of water. The water is then treated at the Marston treatment plant.	Oral communication with Qunetin Hornbeck, geologist, Denver Water Board.

son and Hart (1980), and McGregor and McDonough (1980).

Exploration and Testing Methods

Exploration and testing methods used to define the surface and subsurface conditions at potential building sites include review of technical literature, surface mapping, and subsurface drilling and/or trenching. Samples are usually taken at regular intervals or at apparent changes of material, and tested to determine their engineering characteristics. Field and laboratory tests are mainly performed in accord with specifications of ASTM (American Society for Testing and Materials) by inhouse labs of private geotechnical firms or by commercial labs on a custom (piece-work) basis. In a few labs, test specifications may differ slightly, or additional non-ASTM tests may be available. Testing is generally performed by trained, supervised technicians.

Laboratory capability ranges from minimal to extensive. The best equipped are the central geotechnical laboratory of the U.S. Bureau of Reclamation, and the rock and soil testing facilities of the Engineering Geology Branch, U.S. Geological Survey in Denver. Geological Survey testing is automated, with test control, data sampling and recording performed by computers. This lab is also developing mobile facilities for appropriate on-site testing, data recording, and radio telemetry of field data (Simpson, 1981).

Some common tests used are Atterberg limits, grain size distribution, dry unit weight, one-dimensional consolidation-swell, and moisture content. The Potential Volume Change (PVC) test was widely used in the past but is not generally used today by Colorado geotechnical engineers (Hart, 1974). The PVC test consisted of a modified floating ring consolidometer in a loading frame with a proving ring. An air-dried, recompacted sample is flooded with water and allowed to swell against the proving ring. After two hours, the moving ring dial is read and converted to a swell index (Hart, 1974).

The primary design tests favored by most local geotechnical engineers for swelling soils are the one-dimensional consolidation-swell test for buildings and the California Bearing Ratio (CBR) swell test for highway subgrades (Hart, 1974; Mock, 1981). Dr. Fu Hua Chen (Chen and Associates) has developed a classification system for swelling soils based on three standard AASHO tests. This system compares the percentage of swell from the consolidation-swell test (1,000 psf (479 N/m^2) surcharge), liquid limit, percentage of the sample finer than the #200 sieve (0.074 mm), and the Standard Penetration Test (SPT) blow count. This system classifies swell as follows (Hart, 1974):

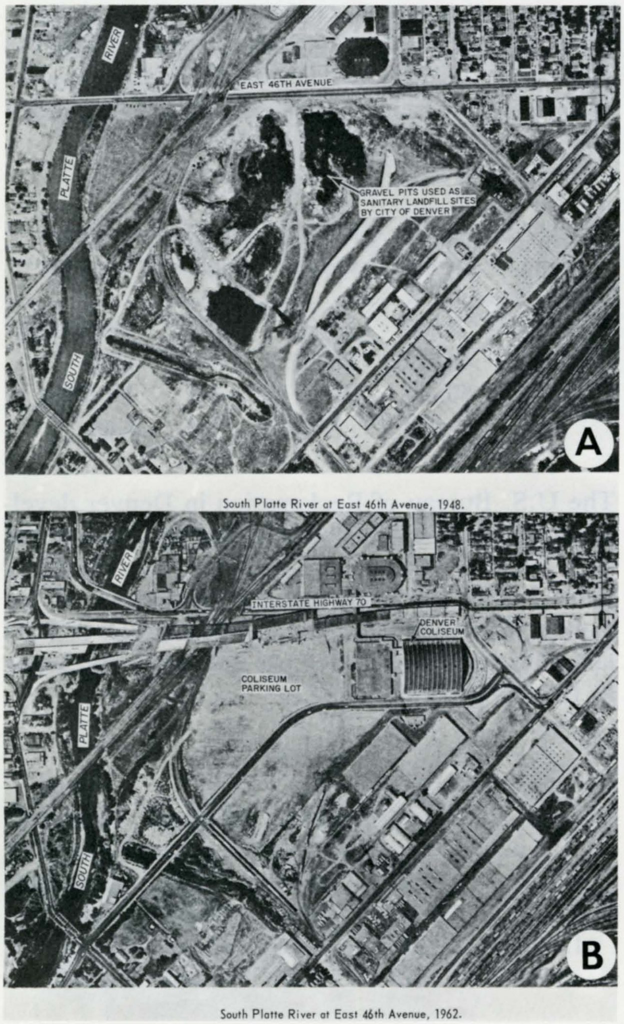
% <#200 Sieve	Liquid Limit	SPT (N) Value	Consolidation Swell (%)	Swell Category
>95	>60	>30	>10	Very high
60–95	40–60	20–30	3–10	High
30–60	30–40	10–20	1–5	Medium
<30	<30	<10	<1	Low

The U.S. Bureau of Reclamation in Denver developed the Holtz-Gibbs classification for swell in the early 1950's. This system compares the plasticity index, shrinkage limit, and the percentage of the sample finer than 0.001 mm to the Bureau of Reclamation swell test at 144 psf (69 N/m^2) surcharge as follows (Hart, 1974):

% <0.001 mm	Plasticity Index (%)	Shrinkage Limit	% Swell	Swell Category
>28	>35	>11	>30	Very high
20–31	25–41	7–12	20–30	High
13–23	15–28	10–16	10–20	Medium
<15	<18	<15	<10	Low

Standard subsurface soil sampling tools used in the Denver metropolitan region are the California (Ring) Sampler, the Standard Split Spoon, the Shelby Tube, and the Continuous Corer. Both the California Sampler and the Standard Split Spoon Sampler are driven into the soil with blows from a 140 lb (64 kg) hammer dropping 30 in. (762 mm). Relatively undisturbed samples two in. (51 mm) in diameter and four to 18 in. (102–457 mm) long can be recovered (Mock, 1981). Larger diameter samples can be recovered by Shelby Tubes and Continuous Coring methods. Soil samples are routinely tested for shear strength, consolidation, and permeability characteristics.

Foundation exploration during the construction of the Denver Coliseum resulted in the development of an early cone penetrometer to test relative densities of coarse alluvial gravels and artificial fill material in a former gravel pit underlying part of the



South Platte River at East 46th Avenue, 1948.

South Platte River at East 46th Avenue, 1962.

Figure 9. Airphotos of Denver Coliseum construction site, (a) in 1948; (b) in 1965 following filling of gravel pit with municipal waste and subsequent urban land uses (Sheridan, 1967).

building site (Peck, 1953). The base diameter of the penetration cone was 2½ in. (64 mm), and the driving hammer assigned a weight of 350 pounds and a fall of two ft (610 mm). The number of blows required for each ft (0.3 m) of penetration was counted, which led to adequate discrimination of artificial fill material from dense gravel layers. Based on these penetrometer results, the location for the structure was moved 50 ft (15 m) east to allow a spread footing foundation to be located uniformly on the upper surface of an extremely dense part of the gravel deposit (Peck, 1953) (Table 3; Figure 9). This sampler has not seen much local use since its first application.

Foundation Types

Typical foundations used in the Denver metropolitan area are spread footings, bearing walls on grade, pads with grade beams, drilled piers (or caissons) with grade beams, and post-tensioned slabs (Figure 10). The type of foundation depends on the size of the structure, and the surface and subsurface conditions of the site. Spread footings and footing walls are most commonly used for smaller structures such as homes and buildings less than four stories high. High rise structures (more than five stories) are usually supported by drilled piers (or caissons) that are founded in bedrock (Table 3). Drilled piers with grade beams have also been very successful in areas where swelling clay is present. They may be straight shaft, straight shaft with shear rings, or belled.

Building on expansive soils in and around Denver has encouraged the use of various engineering and design treatments. Lightly loaded structures built over soils with low swell potential often use spread footing foundations. With slightly higher swelling potential, footing walls or grade beams supported by pads are utilized (Hart, 1974). Over moderate to highly swelling soils, small-diameter, heavily-loaded, straight-shaft piers are extended to a depth where moisture changes are minimal. The piers are commonly used in conjunction with grade beams. Piers carry structural loads by skin friction along their surface length and by end bearing pressure at its base. Piers are commonly 10 to 20 ft (3–6 m) long and extend three to eight ft (0.9–2.5 m) into firm bedrock. This design is common in Denver because it has been very successful in expansive soils. Many local contracting firms specialize in drilled pier foundations, making this an economical design. Belled pier foundations are not extensively used because the enlarged pier bottom reduces contact bearing pressures on the potentially expansive materials. In the 1950's through the 1960's, shear rings consisting of enlarged zones placed at regular intervals along the piers were used. It was believed that this design increased the friction bearing capacity; however, later tests showed that it usually did not make an appreciable difference; the practice has generally been discontinued.

In highly expansive soils, structural floors are supported with grade beams and piers. A void space is left beneath the floor system to eliminate heaving damage. Edge-stiffened or post-tensioned slabs have been in limited use around Denver. Chemical

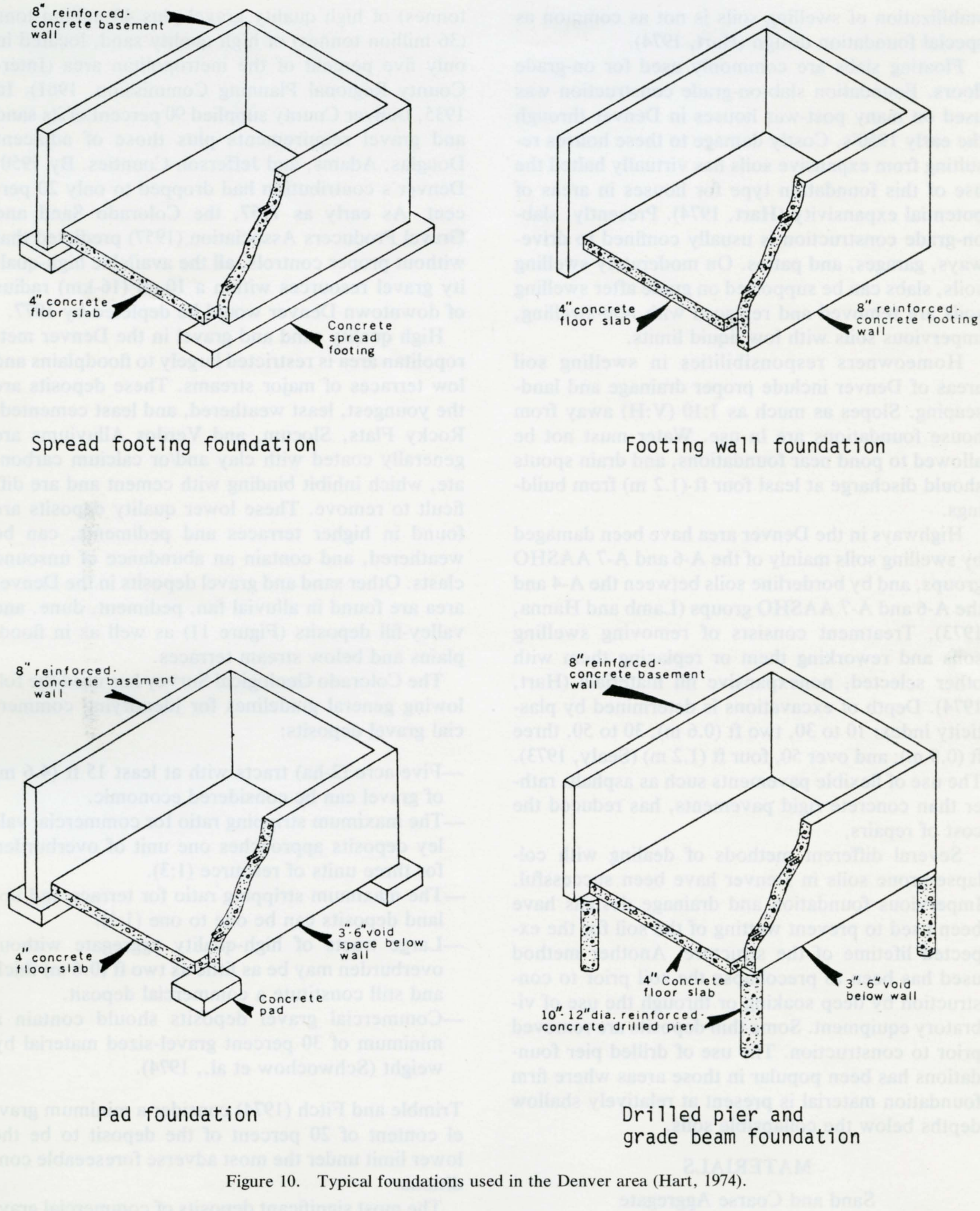


Figure 10. Typical foundations used in the Denver area (Hart, 1974).

stabilization of swelling soils is not as common as special foundation design (Hart, 1974).

Floating slabs are commonly used for on-grade floors. Foundation slab-on-grade construction was used on many post-war houses in Denver through the early 1950's. Costly damage to these houses resulting from expansive soils has virtually halted the use of this foundation type for houses in areas of potential expansivity (Hart, 1974). Presently, slab-on-grade construction is usually confined to driveways, garages, and patios. On moderately swelling soils, slabs can be supported on grade after swelling soils are removed and replaced with non-swelling, impervious soils with low liquid limits.

Homeowners responsibilities in swelling soil areas of Denver include proper drainage and landscaping. Slopes as much as 1:10 (V:H) away from house foundations are in use. Water must not be allowed to pond near foundations, and drain spouts should discharge at least four ft (1.2 m) from buildings.

Highways in the Denver area have been damaged by swelling soils mainly of the A-6 and A-7 AASHO groups, and by borderline soils between the A-4 and the A-6 and A-7 AASHO groups (Lamb and Hanna, 1973). Treatment consists of removing swelling soils and reworking them or replacing them with other selected, nonexpansive fill materials (Hart, 1974). Depth of excavations is determined by plasticity index: 10 to 30, two ft (0.6 m); 30 to 50, three ft (0.9 m); and over 50, four ft (1.2 m) (Sealy, 1973). The use of flexible pavements such as asphalt, rather than concrete rigid pavements, has reduced the cost of repairs.

Several different methods of dealing with collapse-prone soils in Denver have been successful. Impervious foundation and drainage designs have been used to prevent wetting of the soil for the expected lifetime of the structure. Another method used has been to precollapse the soil prior to construction by deep soaking or through the use of vibratory equipment. Some thin deposits are removed prior to construction. The use of drilled pier foundations has been popular in those areas where firm foundation material is present at relatively shallow depths below the collapsible soils.

MATERIALS

Sand and Coarse Aggregate

The Denver metropolitan area was originally endowed with nearly 900 million tons (816 million tonnes) of high quality gravel plus 40 million tons (36 million tonnes) of high quality sand, located in only five percent of the metropolitan area (Inter-County Regional Planning Commission, 1961). In 1935, Denver County supplied 90 percent of its sand and gravel requirements plus those of adjacent Douglas, Adams, and Jefferson Counties. By 1950, Denver's contribution had dropped to only 20 percent. As early as 1957, the Colorado Sand and Gravel Producers Association (1957) predicted that without proper controls, all the available high-quality gravel resources within a 10-mi (16-km) radius of downtown Denver would be depleted by 1977.

High quality sand and gravel in the Denver metropolitan area is restricted largely to floodplains and low terraces of major streams. These deposits are the youngest, least weathered, and least cemented. Rocky Flats, Slocum, and Verdos Alluviums are generally coated with clay and/or calcium carbonate, which inhibit binding with cement and are difficult to remove. These lower quality deposits are found in higher terraces and pediments, can be weathered, and contain an abundance of unsound clasts. Other sand and gravel deposits in the Denver area are found in alluvial fan, pediment, dune, and valley-fill deposits (Figure 11) as well as in floodplains and below stream terraces.

The Colorado Geological Survey has used the following general guidelines for identifying commercial gravel deposits:

—Five-acre (2-ha) tracts with at least 15 ft (4.6 m) of gravel can be considered economic.
—The maximum stripping ratio for commercial valley deposits approaches one unit of overburden for three units of resource (1:3).
—The maximum stripping ratio for terrace and upland deposits can be one to one (1:1).
—Large tracts of high-quality aggregate without overburden may be as little as two ft (0.6 m) thick and still constitute a commercial deposit.
—Commercial gravel deposits should contain a minimum of 30 percent gravel-sized material by weight (Schwochow et al., 1974).

Trimble and Fitch (1974) consider a minimum gravel content of 20 percent of the deposit to be the lower limit under the most adverse foreseeable conditions.

The most significant deposits of commercial gravel are located along the South Platte River and Clear Creek, and in the Rocky Flats alluvial fan located

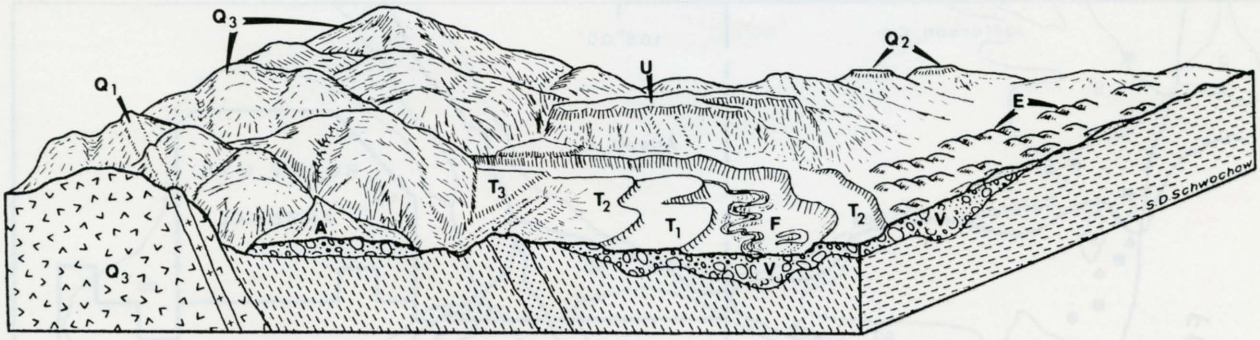


Figure 11. Idealized block diagram showing geomorphic relations among aggregate-bearing landforms. Lowland forms include: valley fill (V), flood plain (F), and terraces (T1—youngest, T3—oldest). Upland forms include gravels (U), alluvial fan (A), and wind-deposited sand (E). Potential quarry-aggregate deposits include fine-grained intrusive igneous rocks (Q1), fine-grained extrusive rocks (Q2), and coarse-grained igneous and metamorphic rocks (Q3) (from Schwochow et al., 1974).

northwest of the city (Figure 12) (Schwochow, 1980). The Rocky Flats alluvial fan contains up to 80 percent quartzite derived from outcrops immediately west of the fan in Coal Creek Canyon. However, this deposit contains a large amount of oversized material. The cobbles and boulders may be suitable for rip-rap, but they are rounded and so may be unstable and hard to place.

Louviers Alluvium is the major source of commercial sand and gravel in Denver, especially along Clear Creek and the South Platte River. Clear Creek Valley contains some of the highest quality gravels available in the Denver area. As a by-product of gravel mining in Clear Creek, operators extract about one ounce of gold for each 1,500 tons (1,361 tonnes) of material processed (Hansen et al., 1976).

Prior to construction of the Cherry Creek Dam and Reservoir in the Southeast Denver metropolitan area (Figure 1), the Bureau of Reclamation conducted extensive tests on three sources of coarse aggregate for concrete appurtenances to the earthfill dam. The coarse aggregates tested included Louviers Alluvium from Clear Creek near Golden, crushed granite from a rock quarry just upstream of Golden on Clear Creek, and crushed basalt from South Table Mountain in Golden (Figure 12). Some test results on these three aggregates are shown in Table 4. Crushed basalt produced a harsh, angular aggregate, and concrete with slightly higher compressive strength, modulus of elasticity, and modulus of rupture. The thermal coefficient of expansion for concrete with basalt aggregate was about eight percent lower than concrete made with the other two aggregates. Concrete made with granite aggregate produced 15 percent less shrinkage on drying than the others. All concretes made with the three aggregates had good resistance to freeze and thaw, produced very good wet and drying durability tests, and had no alkali-aggregate reaction (Hickey, 1950).

The Denver Hilton Hotel in downtown Denver cost $20 million and was completed in 1960 (Figure 1). Its most striking feature is the grill-work of precast concrete framing the exterior walls. All the aggregate used in the facing consisted of pea gravel

Table 4. *Test results of coarse aggregate from the Denver Metropolitan area.*

	Louviers Alluvium (Clear Creek)	Granite (Clear Creek Canyon)	Basalt (South Table Mt.)	Glen-non ls (Lykins Fm)	Ft. Hays ls (Niobrara Fm)
Sp. gr.	2.65	2.68[a]	2.73[a]		
24 hr absorp (%)	0.7	0.3[a]	0.9[a]		
Los Angeles abrasion test, %loss, 100 rev.	12.3	8.6[b]	5.9[a]		
% loss 500 rev. (35% loss limit)	41.2[a]	32.2[b]	27.4[a]	44[d]	24.4[d]
Magnesium sulfate soundness test, % loss, 5 cycles (10% loss limit)	9.8[c]	4.8[b]	13.0[b]		

(From Hickey, 1950.)
[a] 2 tests.
[b] 3 tests.
[c] 4 tests.
[d] Van Horn, 1976.

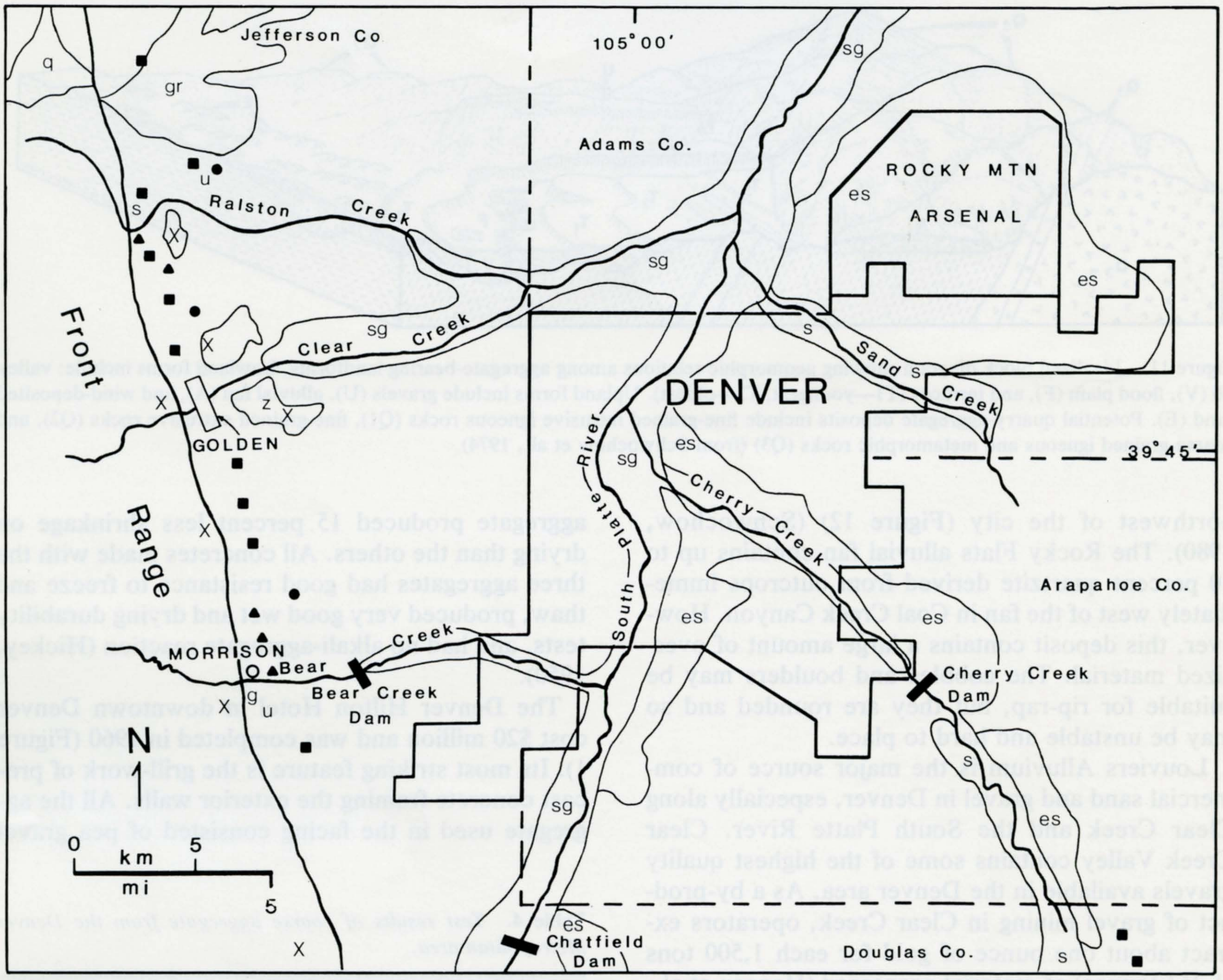


Figure 12. Generalized location of economic mineral resources, Denver metropolitan area. q = quartzite; x = igneous and metamorphic rock quarries; gr = gravel in Rocky Flats alluvial fan; es = eolian sand; sg = sand and gravel; s = silica sand; g = gypsum; z = zeolites; ■ = clay; ▲ = limestone; u = uranium; ● = coal.

excavated and screened from the Broadway Alluvium underlying the construction site. This gravel was used because of its light pink color, soundness, resistance to weathering, and durability. Completed concrete wallings were acid-etched to expose the gravel aggregate (Anonymous, 1959).

Major sand resources occur along Sand and Cherry Creeks and the South Platte River. The material is used for plaster, cement, mortar, blasting, filtration, golf course sand traps, and concrete sand (Schwochow et al., 1974).

The Denver metropolitan area uses more than twice the per capita national average tonnage of sand and gravel, with a value exceeding $22 million per year (Soule, 1974; U.S. Department of Housing and Urban Development, 1978). The metropolitan use represents 41 percent of the state's total sand and gravel production. In 1977, the average price of sand and gravel ($2.00/ton) was double that of 1967, while the price of crushed rock aggregate increased only 44 percent to $2.53/ton (Schwochow, 1980).

Because of the widespread distribution of sand and gravel deposits and the low unit value of the product, industry must be locally oriented in its production and consumption. Unfortunately, many high-quality deposits are now inaccessible in the immediate Denver area because of encroachment by conflicting land uses (Figure 13). Four times as much aggregate has been lost through expansion of

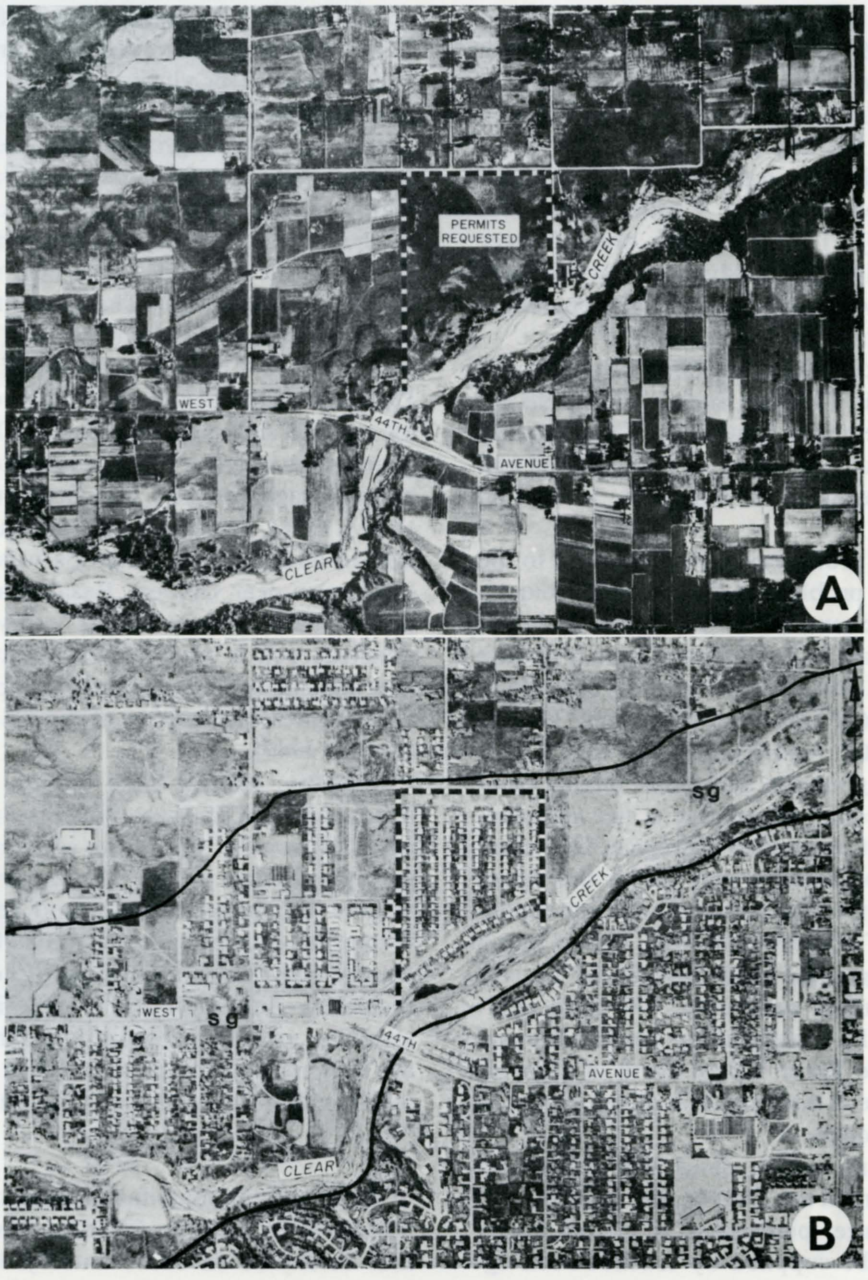


Figure 13. This area (A) is underlain by 20 ft (6 m) of high quality sand and gravel. Three attempts were made in the 1940's to obtain operating permits to mine this land. All requests were denied because of protests from local residents. After the third denial, the land owner sold the property to a housing developer; and as shown (B), the sand and gravel resource has been permanently lost (Sheridan, 1967) (see Figure 1). The principal area of sand and gravel (sg) is outlined in B.

suburbs into areas containing usable deposits than has been consumed in construction (Sheridan, 1967). Well over one-third of the Clear Creek resources have been lost to development in two of Denver's western suburbs, Arvada and Wheatridge. Along Cherry Creek only 10 million tons (9 million tonnes) of the original 30 million tons (27 million tonnes) of sand were mined before encroachment rendered the remaining two-thirds of the resource inaccessible (Inter-County Regional Planning Commission, 1961). The pools of Chatfield and Bear Creek Dams, two recently completed flood-control structures, have precluded the use of enormous quantities of high-quality sand and gravel on the South Platte River and Bear Creek. The remaining large resources of gravel in the Denver area lie to the north of the city in Adams County along the South Platte River from the confluence of Clear Creek north for approximately 11 miles (Figure 12; Schwochow, 1980). These deposits are of lower quality than deposits previously mined in the Denver areas since they contain a smaller percentage of gravel-sized stones, and more sand.

As a consequence of lobbying efforts by sand and gravel producers, in 1973 the State of Colorado enacted legislation requiring that areas of high-quality commercially-extractable deposits be identified and that land use be regulated to insure the protection of this resource.

Local aggregate producers have responded to the resource shortage problem in Denver with four alternatives (Schwochow, 1980). One company began operating a unit train to bring gravel from a pit and loading site on St. Vrain Creek near Lyons, Colorado, about 45 mi (72 km) north of Denver. The 32-car train has a total capacity of 3,200 tons (2,903 tonnes) and hauls gravel to an asphalt mixing plant in Denver. The second alternative is the manufacture of light-weight, expanded aggregate. One company in Denver operated a clay pit in the upper member of the Pierre Shale and an adjacent expansion plant south of Boulder until 1976. Future large-scale expanded aggregate production in the Denver area must wait further evaluation. The third alternative is to mine the lesser-quality sand and gravel in the South Platte River Valley north of Denver. The last alternative is the long-term development of crushed rock aggregate.

The rapidly diminishing sand and gravel resources along rivers in the Denver area indicate that an increasingly larger percentage of coarse aggregate will have to be supplied by crushed rock aggregate (Schwochow, 1980). Rock for crushing in the Denver area consists of Precambrian granite gneisses and schists, quartzite, and Tertiary basalts and monzonite (Figure 12).

Granite gneisses and schists mined for coarse aggregate in the Denver area are all quarried in the Front Range west of the city in Jefferson County. Most crushed rock quarries are located at or near the mouths of canyons because of available transportation routes and proximity to markets. Many are located along major north-west trending faults, long inactive, in the mountain front where brecciation of the rock by faulting has performed the "primary crushing," thus reducing production costs. These quarries produced rock for concrete aggregate, road base, ballast, asphalt binder, and rip-rap. Generally, coarser-grained metamorphic rocks are more satisfactory for crushed-rock aggregate than thinly splitting, highly schistose rocks (Trimble and Fitch, 1974). In the early 1970's, one quarry two mi (3 km) south of Golden provided most of the rip-rap for Chatfield Dam. The quartzite that crops out in a northeast trend about two mi (3 km) wide near the mouth of Coal Creek north of Denver (Figure 12) is one of the best potential sources of high-quality crushed rock aggregate in the Denver area. The quartzite is very hard and crushes to produce clean, angular fragments and very little dust (Schwochow et al., 1974). Basaltic rocks are quarried from extrusive and intrusive outcrops west and northwest of Denver near Golden. Basalt was quarried from South Table Mountain as early as 1905. The crushed rock is used for road materials, concrete and asphalt aggregate, and rip-rap, including that used in the construction of the Cherry Creek Dam (Argall, 1949).

Recently, several large mining operations have been proposed in these igneous and metamorphic rocks. However, the future of crushed-rock aggregate production in the Denver area is uncertain, despite the increasing demand for the resource. Numerous mining permits have been denied by county governments because of concerns of local residents. Alteration and weathering zones, slope stability, esthetic, zoning, and land-use problems are serious limiting factors which will have to be addressed in the instance of future mining.

Clay

Brick and tile manufacturing is one of the oldest industries in Denver. Thomas Warren started the first brickyard in 1859, and by 1860 some brick buildings were in existence; but the majority of structures were wood frame, even though bricks were cheaper than wood (Smiley, 1901). In April of 1863, a fire burned out much of the Denver business area. Seventy buildings were destroyed and scores of residents were homeless. Damages totaled $350,000. A city ordinance subsequently was passed prohibiting construction of wood-frame buildings, and the city rebuilt with brick. The "brick code" in Denver was repealed shortly after World War II for all parts of the city except the downtown core area where wood-frame buildings are still prohibited. Quaternary loess and cohesive alluvium were the major sources of common brick material in early Denver (Ries, 1927).

Refractory and structural clays recently mined in the Denver area are primarily Cretaceous and younger in age, but small amounts were mined from older formations. Clay-producing units have included the Dakota, Benton, Pierre, Laramie, Arapahoe, and Dawson Formations (Crosby, 1977). The Dakota Formation is the sole source of refractory clay in the Denver area, but today, most of the best quality and easily mined refractory deposits have been exhausted (Waage, 1952, 1961).

Demand for refractory clays began in the 1860's with the construction of the first smelters to process ores from the mountains west of Denver (Yingst, 1961). It is ironic that early ore smelters in Golden were located within sight of hogbacks containing high-quality refractory clays, while refractory brick for the smelters was being imported from Wales (Lakes, 1909). However, today refractory clays in the Denver area cannot economically compete with out-of-state clays (Crosby, 1977).

Nearly all clay produced in the Denver area goes to structural clay products such as bricks, tiles, flue liners, flower pots, low-grade ceramics, and sewer pipes. The major non-refractory clay source in the Denver area is the Laramie Formation. Some Laramie clay pits south of Golden have been used for landfill sites (Van Horn, 1976). Structural clays from the Dawson Formation south of Denver are sufficiently valuable that economic hauling distance for this clay to Denver plants is greater than other clays mined in the area (Crosby, 1977; Figure 12).

Several hundred thousand tons of the upper Pierre Shale northwest of Denver were mined yearly between 1961 and 1976 for expanded aggregate. The shale bloated two to three times its original volume when crushed, and rapidly heated to 1,800 to 2,200°F (U.S. Geological Survey, 1968). It had a density of 30 to 60 lbs/ft^3 (481–961 kg/m^3) and had good structural strength and thermal- and acoustical-insulating properties.

Building Stone

Dimension stone was originally used in Denver pioneer days as foundation blocks to support the full weight of structures. Today, most use in Denver is as decorative veneers, monuments, paving blocks, flagging, curbing, landscaping, and window sills. Among the most popular building stones that have been used in the Denver area are Lyons Sandstone whose slabs are quarried for flagstone curbs, and veneer strips for building facings; Dakota Sandstone used for dimension stone and lichen-covered landscape rock; Yule Marble from the western slope of Colorado for dimension stone, floorings, and steps; and Castle Rock Rhyolite used as rough-dressed dimension stone, window sills, door arches, and garden walls. Table 5 lists some prominent buildings in Denver and the kind and source of stone used in their construction.

Table 5. *Examples of some building stones in the Denver area.*[a]

Stone	Structure
Castle Rock Rhyolite, Douglas Co.	Union Depot, Denver St. Elizabeth Church, Denver Trinity Church, Denver Old Republican Building, Denver Old Board of Trade Building, Denver Old City Hall, Denver University Hall (Old Main), University of Denver
Yule Marble, Gunnison Co.	State Capitol Building, Denver Main Post Office, Denver Federal Reserve Bank, Denver U.S. Customs House, Denver Colorado State Capitol Annex
Salida Travertine, Chaffee Co.	Interior of City and County Building, Denver Denver National Bank, Denver
Wellersville Travertine, Fremont Co.	Denver General Hospital, Denver Gates Rubber Company, Denver
Cotopaxi Granite, Fremont Co.	Base of City and County Building, Denver State Office Building, Denver
Gunnison ("Aberdeen") Granite, Gunnison Co.	State Capitol Building, Denver State Museum Building, Denver
Platte Canyon Granite, Jefferson Co.	Equitable Building, Denver
Masonville Granite Larimer Co.	U.S. Mint Building, Denver
Lyons Sandstone Boulder Co.	Boston Building, Denver Masonic Temple Building, Denver Central Presbyterian Church, Denver
Arizona sandstone	Brown Palace Hotel, Denver

[a] Compiled from: U.S. Geological Survey, 1968; Argall, 1949; Harvey, 1946; Smiley, 1901; Sharps, 1963.

The State Capitol building in downtown Denver is an interesting study of the use of a variety of native Colorado building stones. In 1889, gray granite from Gunnison, Colorado, was selected over seven other proposed granites as the building stone for the State Capitol building. The Gunnison Granite was named "Aberdeen" after the famous Scottish quarry (Hunter, 1914). The rock was to be supplied free, resulting in a savings of $0.5 million over the original design calling for sandstone (Moore and Borland, 1947). The Denver and Rio Grande Railroad built six mi (10 km) of track from Gunnison to the quarry at the expense of the railroad (Moore and Borland, 1947), and the stone was then shipped by rail. The granite quarry employed 150 stone cutters, with an equal number of masons working in Denver. About 280,000 ft^3 (7,930 m^3) of rock was quarried for the capitol building, and the Gunnison ("Aberdeen") Granite blocks were selected to be used for the drilling contest during the 1891 mining congress in Denver. Work on the capitol was interrupted temporarily in 1891 by a strike by quarrymen demanding a nine-hour work day and Sundays off, rather than the customary 10-hour, seven-day shifts of the time (Moore and Borland, 1947). The state capitol building was completed in 1894 at a cost of $3.4 million. The "Aberdeen" quarry was reopened a year later to supply stone for the exterior steps of the capitol building, and again in 1911–1912 to supply stone for the State Museum Building in Denver.

Yule Marble was used for the State Capitol Annex, as well as the interior stairs and floors of the capitol building. This was done with native marble even though Italian marble could be bought and shipped to Colorado more cheaply than Yule marble could be mined and transported to Denver from the mountains (Colorado Department of Education, 1979). Colorado rose onyx from Beulah (Pueblo County) was used as wainscoating throughout the interior of the capitol. This onyx took seven years to install and cost $120,000 (Colorado Department of Education, 1979).

Limestone, Silica Sand, Gypsum, Zeolites, Organic Soils

Small amounts of limestone have been mined from Paleozoic and Mesozoic rocks outcropping in the foothills north, west, and south of Denver. The Glennon Limestone member of the Lykins Formation was mined prior to 1960 for agricultural lime (Scott, 1963). The Fort Hays Limestone member of the Niobrara Formation is nearly pure and has been mined, crushed, and used as smelter flux in foundries in Golden and Denver (Scott, 1962; U.S. Geological Survey, 1968), and as agricultural and mortar lime (Figure 12). Fort Hays rock is mined, along with the Smoky Hills Shale member of the Niobrara Formation, for portland cement near Lyons, Colorado, 45 mi (72 km) northwest of Denver (Crosby, 1977).

Silica sand is used in the Denver area as molding sand for iron foundry works, core sand, glass, and cement manufacture (Scott, 1963; Argall, 1949; Crosby, 1977). The source rocks are the Dakota Group sandstones, Lyons, and Lykins Formation (U.S. Geological Survey, 1968; Figure 12).

The first reported production of gypsum in Colorado was from the Ralston Creek Formation at Morrison, about 10 mi (16 km) southwest of Denver, which was worked before 1875 (U.S. Geological Survey, 1968; Figure 12). Small amounts of gypsum were also mined south of Denver in Douglas County and north of Denver from the Lykins Formation for use in plaster, Portland cement, retardant, and as soil conditioner (Argall, 1949; Williamson, 1963; Crosby, 1977).

Zeolites were reported from the Table Mountains in Golden in 1878 where they occur in cavities and veinlets as granular masses as alteration products of silicate minerals in basalt (Figure 12; Gude, 1980; Emmons et al., 1896). While this is a valuable mineral collecting location, no economic production has occurred there.

Organic soils consist primarily of young surficial deposits, especially Piney Creek, and younger alluvium, with humus-rich A soil horizons. These are used in the Denver area as topsoil for landscaping, and sold for soil conditioning material (Scott, 1963).

Coal, Uranium, Oil, and Gas

The entire City of Denver and its suburbs are underlain by subbituminous coal in Cretaceous rocks that lie at a depth less than 3,000 ft (914 m). Some eastern suburbs, such as Aurora, are underlain by lignite at depths less than 150 ft (46 m) (U.S. Geological Survey and Colorado Geological Survey, 1977). However, urbanization has precluded mining in nearly all areas except near the foothills where deposits are nearest the surface and urban development is minimal. Subbituminous coal was mined from the Laramie Formation west of Denver as late as 1950 (Scott, 1962), but mining has now ceased (Figure 12).

More than 100 uranium claims exist in sedimentary rocks in the foothills west of Denver, ranging in age from late Paleozoic to Cretaceous (Scott, 1963). The highest grade ores are found in Cretaceous sedimentary rocks, primarily the Dakota

Sandstone, about one and one-half mi (2.3 km) east of the Front Range near Morrison and Golden (Figure 12). Ores of 0.19–0.26 percent U_3O_8 have been mined from the Dakota Sandstone (Sims and Sheridan, 1964). Deposits typically are primary in origin, and were precipitated as veins along fault zones by ascending hydrothermal solutions (Sims and Sheridan, 1964). Uranium ores with concentrations of 0.35 percent U_3O_8 have also been found in Laramie deposits of coal and adjoining sandstone and claystone in the old Leyden coal mine northwest of Denver in Jefferson County. This mine has been converted to natural gas storage by the Public Service Company of Colorado.

Significant oil and gas fields occur in Cretaceous rocks just north and east of Denver, but most production occurs outside the Denver metropolitan area (U.S. Geological Survey and Colorado Geological Survey, 1977). Non-producing oil seeps have also been discovered west of Denver in Mesozoic sedimentary rocks and Precambrian igneous and metamorphic rocks (Van Horn, 1976).

GEOLOGIC CONSTRAINTS

The Denver metropolitan area has a number of geologic constraints (Hansen, 1976). One of the most significant, widespread, and costly is swelling soils. One Denver geotechnical engineer estimated that one out of 10 houses in Denver suffers, or will suffer, from swelling soil problems; and, in extreme areas, one of three new houses built will have problems (Chen, 1980). This occurs partly because Denver's recent housing boom has pushed construction into problem areas that a few years ago would not have been used.

Swelling soils are generally caused by expansion due to wetting of certain clay minerals (usually montmorillonite) in dry soils. Semi-arid areas like Denver, with pronounced seasonal variations in soil moisture, usually experience the most severe swelling soil problems provided the proper clay minerals are present. Both shrinkage and swelling can occur with moisture variation, and either can cause damage to streets and structures. In the Denver area, swelling has caused most of the damage (Hart, 1974).

Many parts of the Denver/Arapahoe Formations, Pierre Shale, and some of the surficial deposits derived from them, contain very highly swelling clays and have caused millions of dollars in damages (Figure 8). Few areas within the Denver metropolitan region are completely free from potential swelling, however deposits with high to very high swell potential are of more limited extent (Figure 8).

In 1970, Ridge Home, a state school for the mentally retarded, required $0.5 million in repairs for cracked walls, floors, ceilings, doors, and window frames, in a building only six yrs old (Figure 1). At Isaac Newton Junior High School (Figure 1), $1 million was spent on repairs for a building only 12 yrs old (Table 3). This expense was equal to the original construction cost of the building.

Subsidence

Another significant geological problem in the Denver area is land subsidence and methane gas accumulation in and near former sand and gravel pits that were mined out and subsequently used for municipal waste-disposal sites (McBroome and Hansen, 1978). These landfills were then graded and converted to various kinds of urban development. Subsidence also has occurred over old coal and clay mines, and from compaction of loess, eolian sand, and organic silts. Hydrocompaction of loess, lateral spreading of eolian sand, and settlement of organic soils have been already discussed under geotechnical characteristics.

Landfills and Methane Gas

Decomposition of organic matter in landfill sites produces a variety of gases, including methane, which is colorless, odorless, and explosive in concentrations greater than five to 15 percent. In June of 1977, two water line construction workers were killed by a methane explosion during construction of water lines near an old trashfill. Figure 14a shows a 1.6 mi (2.6 km) stretch of the South Platte River floodplain in central Denver. This reach was virtually one continuous sand and gravel mining operation in 1949 (Figure 1). With the completion of mining in this area in the 1950's, the pits were used as landfills by the City of Denver, and filled primarily with residential and commercial wastes. No effort was made to compact the fill, nor to place daily or even less frequent earth covers on the debris. Refuse fill ranged in thickness from 20 to 40 ft (6–12 m); and when filled, a three-ft (1 m) cover of clean earth was placed over the entire landfill area. Figure 14b shows the same area 15 years later in 1965. Many of the landfill sites have been utilized for industrial, commercial, and private buildings. In 1978, methane gas concentrations of as much as 62 percent gas by volume of sample were discovered

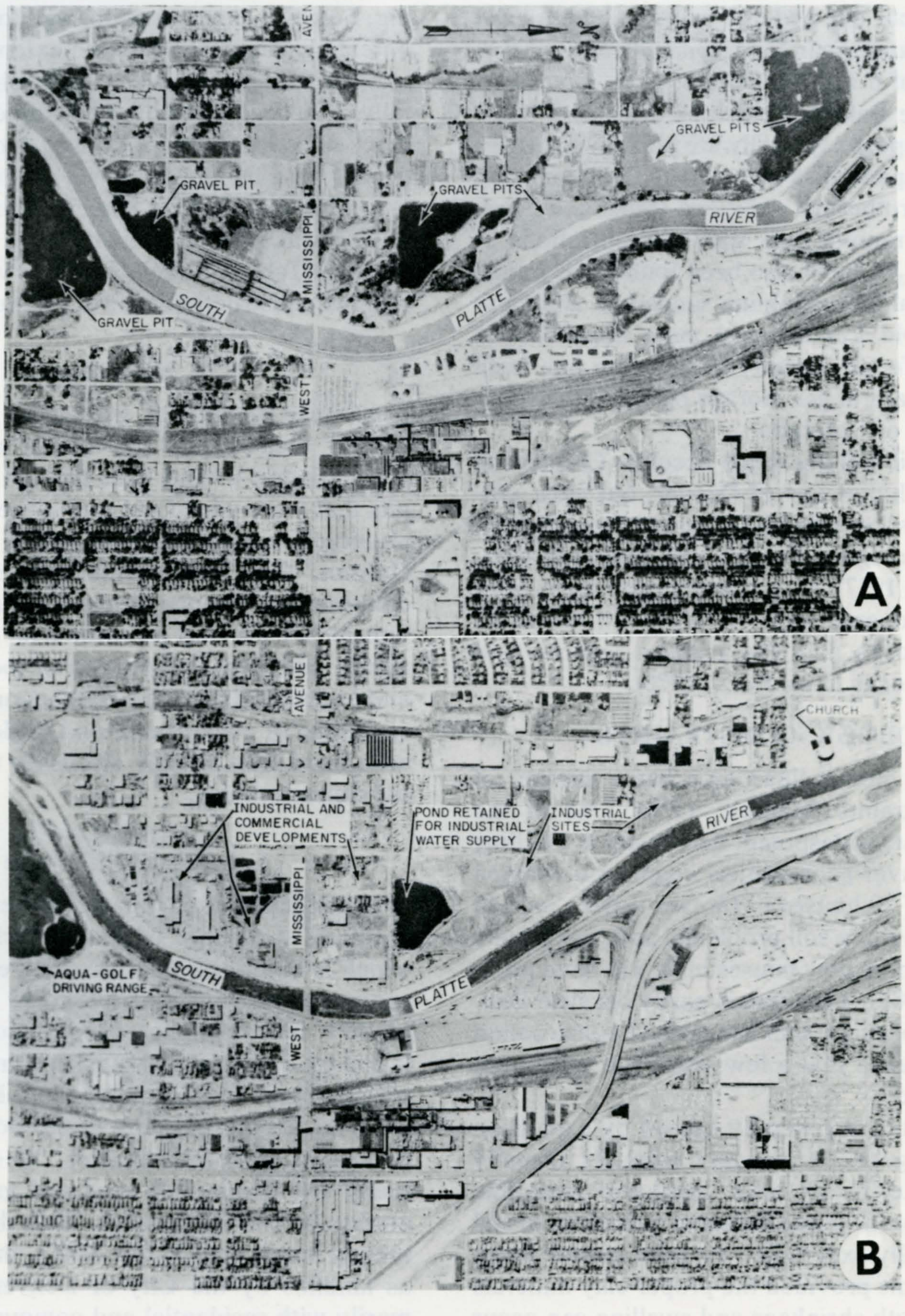


Figure 14. Airphotos of a reach of the South Platte River in Denver, (A) in 1949, and (B) in 1965 following filling of gravel pits with municipal wastes and subsequent urbanization (Sheridan, 1967). The location of the airphotos is shown in Figure 1.

at shallow depths in areas of landfill deposits (Raymond Vail and Associates, Inc., 1979).

One of the highest methane concentrations was found in the church pictured in the upper right-hand corner of Figure 14b. Extensive settlement has resulted in severe damage to basement floors and three ft (1 m) of separation between foundation walls and the basement floor surface. Figure 15 is a photo of some visible exterior subsidence at this structure.

The Cedar Run apartment complex in southeast Denver is built on the site of a sand and gravel pit excavated through Louviers Alluvium in a terrace along the north bank of Cherry Creek (Figure 1).

Between 1950 and 1964, the area served as a landfill for the City of Denver. The property was subsequently purchased and developed into an apartment house complex. The buildings were constructed on caissons extending through the landfill to undisturbed soils below. The structures have experienced only minor distress, but landscaped areas and parking lots exhibit extreme non-uniform settlement. Buried water and sewer lines serving the complex have ruptured on numerous occasions. Structural distress to basement parking lots, pavement slabs, and basement walls has permitted migration of hazardous amounts of methane gas into buildings.

Place Junior High School was originally designed to be located partly on waste fill along Cherry Creek. Foundation engineers recommended the removal of all trash beneath the foundations, and subsequent backfilling with compacted clay soils. Some visible subsidence has since occurred in the street in front of the building, and methane gas has been found in buildings next to the school, but the school itself has been free of foundation and gas problems.

In Denver, design accomodations for structures built over landfills with methane gas problems have included: (a) a constant ventilation system, (b) methane gas alarm systems, and (c) routine inspection of all structures built over former landfills (Raymond Vail and Associates, Inc., 1979).

Clay and Coal Mine Subsidence

Abandoned clay pits have been routinely filled in the Denver region, notably those in the Laramie Formation west of the Colorado School of Mines in Golden. By 1980, extensive infilling with fly ash and flue gas desulfurization waste from the coal-fired Arapahoe generating station in Denver was underway (Figure 16).

Apartment buildings have subsequently been built over some of the older fills. When founded on the sandstone rib walls of the clay pits, the buildings have been little affected by compaction and subsidence. At least one building suffered structural damage when constructed on footings three ft (1 m) deep founded on thick artificial fill overlying a clay pit (Van Horn, 1976). Engineers concluded the foundation failure was caused by the inter-rib earthfill not being properly compacted right next to the ribs because of the two to three ft (0.7–1 m) width over which a sheepsfoot roller cannot reach adjacent to a vertical face. This led to settlement of part of the building foundation which broke sewer pipes.

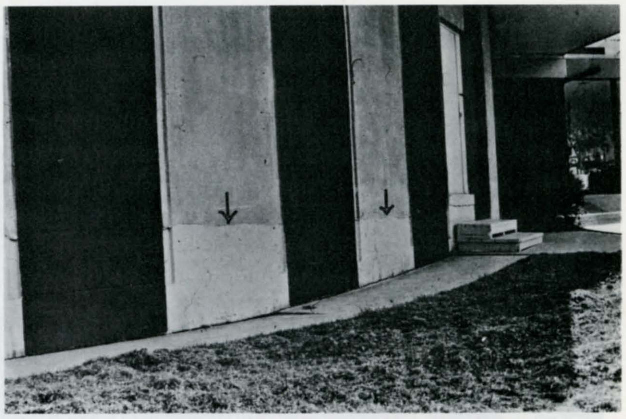


Figure 15. Church shown in Figure 14B showing three ft (1 m) of subsidence of ground surface on outside of building. Original ground surface marked by arrows. Note the temporary stair box below the exit. (Photo taken in April, 1980.)

The broken sewers caused piping of fine sediment from the earthfill down into an old clay-mine access tunnel close below. Enough support was piped out to cause structural failure. The solution was to support building walls with structural steel that extended from one sandstone rib to another, or from one rib to tested compacted earthfill on in situ clay beds that had no adits below (Simpson, 1981).

Numerous underground coal mines in Cretaceous sedimentary rocks west of the City of Denver were worked from the early to mid-1900's. An extensive engineering geologic report on the Boulder-Weld Coal Field northwest of the Denver metropolitan area was produced for the Colorado Geological Survey in 1975 (Amuedo and Ivey, Inc., 1975). This report documented extensive subsidence and property damage over old underground coal mines. In late summer 1981, it was realized that a large shopping center to be built in the southwest Denver area was located over old underground coal mines in the Laramie Formation (Figure 1). A subdivision located over the mines was platted in 1956 and county records show no reference to the coal mines. One contractor who built houses in the subdivision thought major problems with concrete driveways and basements were the result of swelling soils when, in fact, the problems may be related to ground instability from mine collapse (Jenkins, 1981). The existence and location of the coal mines are discussed and clearly located in the USGS report on the geology of the Littleton Quadrangle (Scott, 1962).

Figure 16. Fly ash slurry disposal as a stabilizing medium for reclamation of abandoned clay pits, Golden, Colorado. The fly ash is delivered by truck, in a wet mixture, over the 15 mi (24 km) distance from the Arapahoe Station of the Public Service Company of Colorado, in Denver. Approximately 3.5×10^3 yd^3 (2.7×10^3 m^3) are produced and delivered each week in a fleet of ten trucks. Mining of the vertically-bedded Laramie Formation clay strata has been going on since about 1876 by members of the Parfet family, who have been managing the fly ash disposal since 1979. Eventual reclamation of the clay pits is planned, with structural foundations designed to span the slurry fills, bearing on the Laramie interbeds (Photograph by Allen W. Hatheway, September 1980).

Mass Movements

A variety of types of mass movements occurs in the Denver area, especially in hilly terrain underlain by Cretaceous and Tertiary fine-grained sedimentary rocks. The probability of slope failure increases significantly where slopes are steeper than 30 percent, and where relief is greater than about 100 to 200 ft (30–61 m). The most significant mass movement hazards exist in the mountains and foothills west of Denver, and south of the city on steep slopes in Douglas County. Steep cut slopes and excavations in some surficial deposits such as eolian sand are also unstable. However, mass movements generally are not a significant problem in the urbanized portion of the South Platte River Valley.

Rockfalls occur south of Denver in the easily eroded shales, mudstones, siltstones, and sandstones of the Dawson Formation, where overlain by a caprock of resistant conglomerate or rhyolite. Rockfalls also occur in the foothills and mountains west of Denver in steep, naturally occurring, or undercut rock slopes of fractured bedrock. Rockslides are found on steep dip slopes of Cretaceous sedimentary rocks in the foothills.

Small earthflows and debris slides also occur south of Denver in areas of steep slopes underlain by clay-rich bedrock and surficial materials (Maberry, 1972a). In the City of Denver, landslides are restricted to clay, silt, and sand-rich colluvial deposits on valley slopes which fail as small rotational slump blocks (Lindvall, 1979b).

Two areas west of the city are the most prone to landsliding in the region—Green Mountain and

North and South Table Mountains. The slopes of Green Mountain are marked by earthflows/debris flows of different ages, presumably post-Pleistocene; some having been active in modern times (Scott, 1972b). The failures on Green Mountain occur in the Green Mountain Conglomerate and underlying Denver Formation.

The flanks of North and South Table Mountains have had a long history of landsliding (Van Horn, 1976). The slopes of the Denver Formation are oversteepened because of a caprock of hard basaltic rock, which results in numerous slumps, rockfalls, and earthflows (Simpson, 1973a, 1973b). Where one road crosses a landslide on the south side of North Table Mountain, the asphalt was estimated to be 13 ft (4 m) thick as successive layers of pavement were added to maintain the road at grade (Conference Field Trip Committee, 1969). A large-area landslide at the north end of North Table Mountain has been estimated to have a total volume of two-thirds to three-fourths mi^3 (2.8–3.1 km^3) (Simpson, 1981).

Conventional methods of mitigating landslide hazards are utilized in the Denver area. These include unloading by grading, drainage provisions, and construction of retaining structures such as buttresses, walls, cast-in-place piles, and tie-back anchors.

Rising Water Tables

In some parts of the Denver area, several hundred homes are plagued by rising ground-water tables and consequent basement flooding. The problem areas are underlain by five to 15 ft (1.5–4.6 m) of permeable surficial deposits above the natural water table, or by an impervious layer of bedrock. The rise in water tables has been attributed to changing of drainage patterns and excessive lawn watering following urbanization. Denver homeowners add an average of 45 in. (1,143 mm) of water to their lawns annually (Shelton and Prouty, 1979), and the recharge to the water table through permeable soils by this method is both rapid, and estimated to be six to seven times more effective than that of natural precipitation (Hamilton and Owens, 1972a). Damages average between $1,000 and $4,000 per affected house. Many such homeowners have had to install sump pumps and shallow dewatering wells.

The basement of the Denver Hilton Hotel in downtown extends 60 ft (18 m) below ground level into the Denver Formation. The ground-water table in the shallow aquifer was just 30 ft (9 m) below street level, and more than two million gallons (7.6 million liters) of water a day was pumped from the foundation site for a period of over two years (Anonymous, 1959).

Flooding

Despite its generally semi-arid nature, an area of the foothills region in Colorado below an altitude of about 7,500 ft (2,286 m) and extending eastward about 50 mi (80 km) onto the Great Plains is subject to very intense cloudburst rainstorms. The usual sources of these cloudbursts are warm, moist Gulf coastal air masses moving northward. Rainfall amounts have been as high as 12 to 14 in. (305–356 mm) in four hours. The magnitude of these storms can be appreciated from the following account of a cloudburst in July of 1896: "The daughter of a rancher was riding on Green Mountain, looking after the stock, when the storm started. By the time she reached the barn, she was practically unconscious on her horse and had to be revived by means used for resuscitating victims of drowning, as the intensity of the rain made it almost impossible for her to breathe." (Follansbee and Sawyer, 1948, p. 22). In a cloudburst in 1921, a horse drowned in an open field (Follansbee and Sawyer, 1948).

The earliest flood in the Denver area occurred in 1844 on the South Platte River. In 1858, Indians told of great floods along Cherry Creek in times past. Figure 17 shows downtown Denver following a flood on Cherry Creek in 1878. We estimate less than 50 people have perished as a result of flooding in Denver since settlement began, but property damage has been very great. Table 6 lists the historic floods of the South Platte River and Cherry Creek. Denver floodplains constitute 30.6 mi^2 (79 km^2) or 10.5 percent of the urbanized area. About 62 percent of this floodplain area has been urbanized (Schneider and Goddard, 1974).

The most disastrous flood in Denver's history occurred on June 16, 1965, when $508 million in damages resulted and six lives were lost. More than 12 to 14 in. (305–356 mm) of rain fell in about four hours in an area south of Denver. Plum Creek, a tributary to the South Platte River draining 302 mi^2 (782 km^2), crested at 154,000 cfs (4,361 cms). The previous maximum known flood was 7,700 cfs (218 cms) in 1945 (Matthai, 1969). The flood peak took two and one-half hours to travel 15 mi (24 km) to the gaging station on the South Platte River at Littleton, where channel and valley storage reduced the crest to 110,000 cfs (3,115 cms). The flood then

Figure 17. Photograph of Larimer Street bridge in downtown Denver, looking southwest, following flood of 1878. (Photo courtesy of Colorado State Historical Society.)

continued toward Denver, and four and three-quarters hours later the flood had traveled 11 mi (18 km) to the gaging station just below the juncture with Cherry Creek (Figure 1) where the attenuated peak discharge crested at 18.66 ft (5.69 m) and 40,300 cfs (1,141 cms) (Matthai, 1969).

The most recent significant flooding in Denver occurred in May of 1973 when steady rains swelled channels and culverts resulting in $50 million in damages (Hansen, 1973). Scour in the South Platte River undermined and destroyed the 15th Street bridge (Table 5).

The devastating flood of June 1965 resulted in two significant achievements in drainage design and control. First, in 1968, the Denver Regional Council of Governments contracted for the preparation of an Urban Storm Drainage Criteria Manual (Wright-McLaughlin Engineers, 1969). Second, the flooding led to the passage of Colorado Senate Bill 202, the Urban Drainage and Flood Control Act of 1969, creating the Urban Drainage and Flood Control District. The District is authorized to set a 0.4 mill tax levy for floodway and floodplain engineering, maintenance, and master planning for Denver and surrounding metropolitan areas. Drainage and flood control are the only responsibilities of the District.

In 1935–1936 Kenwood Dam, or Sullivan Barrier, was constructed on Cherry Creek at a point now located just outside the southeast city limits of Denver. The dam cost about $800,000, of which Denver paid approximately 75 percent. However, during the construction of this dam, the infamous storm of May 30–31, 1935, occurred in the adjoining Republican River Basin. This storm far exceeded any other in historical times, and the Kenwood Dam was considered underdesigned and obsolete before it was completed (Costa, 1978). In 1950 the U.S. Army Corps of Engineers completed the present Cherry Creek Dam and Reservoir at a cost of $14.8 million (Figure 1; Table 7). The dam is an earthfill structure, 14,300 ft (4,359 m) long and 140 ft (42.7 m) high, dwarfing the pre-existing Kenwood Dam (Figure 18). In 1965 the dam completely impounded a flood of 59,000 cfs (1,671 cms) along Cherry Creek which would have caused an estimated $130 million in damages to Denver downstream. Unfortunately, encroachment and development along the channel downstream and along the spillway outfall has re-

Table 6. *Floods along South Platte River and Cherry Creek.*

Date		Stream	Peak Q cfs	Note
	1844	So. Platte River	?	Earliest historical flood
May	1864	Cherry Creek	20,000 ?	19 killed; all bridges across Cherry Creek destroyed
June	1864	So. Platte River	?	Heavy rain on snow in upper basin
May	1867	So. Platte River	?	Greater than 1864 flood
May	1876	Cherry Creek	11,000 ?	—
		So. Platte River	?	Great destruction
May	1878	Cherry Creek	?	Less than 1864 flood; all bridges across creek destroyed
May	1885	Cherry Creek	20,000	Largest historical flood
June	1894	So. Platte River	14,000	—
July	1912	Cherry Creek	11,000–15,000 ?	Over ½ million dollars damages in Denver
June	1921	So. Platte River	8,790	500 homes inundated in Denver
Aug	1933	Cherry Creek	16,000	Failure of Castlewood Dam; $800,000 damages in Denver
Sept	1933	So. Platte River	22,000	—
June	1965	So. Platte River	40,300	Six drowned; $300 million damages in Denver. Largest historical flood.
May	1973	So. Platte River	18,500	$50 million damages; 1.1 times 50-year flood

duced the flood control benefits of the dam (Costa, 1978).

After the 1965 flood, the $85 million Chatfield Dam was constructed on the South Platte River just south of Denver (Figure 1) for flood control and incidental recreation (Table 7). Construction was started in 1967 and was completed in 1977. In 1979 Bear Creek Dam on Bear Creek, just east of the mountain front (Figure 1), was finished. This completed the damming of most major streams draining through the Denver area (Table 7). Only Clear Creek remains undammed.

SEISMICITY

Colorado has long been considered an area of low seismicity, with only a minor potential for future damaging earthquakes (Algermissen, 1969). Recent investigations, however, have discovered several active faults that are capable of generating future earthquakes and numerous other faults that are suspected of being active (Kirkham and Rogers, 1981; Shaffer, 1980; Ostenaa et al., 1980). These investigations suggest Colorado is a moderately active earthquake area; and, in time, larger earthquakes than have yet been experienced can occur (Simon, 1969).

Modern man has occupied Colorado for about 120 years, and during this period hundreds of earthquakes have been noted. Over the past few decades, Colorado earthquakes have been detected, located, and measured by a small number of seismographic instruments. Most earthquakes have been minor, but some exceeded Richter magnitude 5, with locally severe ground shaking. Father Armand W. Forstall installed the first seismograph in Colorado at Regis College in Denver in 1909. This instrument has provided valuable data but has op-

Table 7. *Major flood-control dams in the Denver metro area.*

	Cherry Creek Dam	Chatfield Dam	Bear Creek Dam (Mt. Carbon)
Date completed	1950	1976	1979
D.A. controlled	386 mi²	3,018 mi²	262 mi²
Type	Earth fill	Earth fill	Earth fill
Height	140 ft	147 ft	179.5 ft
Length	14,300 ft	13,340 ft	5,300 ft
Vol. of fill	13,240,000 yd³	14,650,000 yd³	11,345,000
Spillway type	Uncontrolled side channel	Ungated concrete chute	Ungated dirt (bedrock) chute
Max. capacity	(185,000 a.f.*) 93,000 a.f.	355,000 a.f.	75,000 a.f.

* When originally built. Urban encroachment has reduced maximum capacity by rendering spillway unusable.

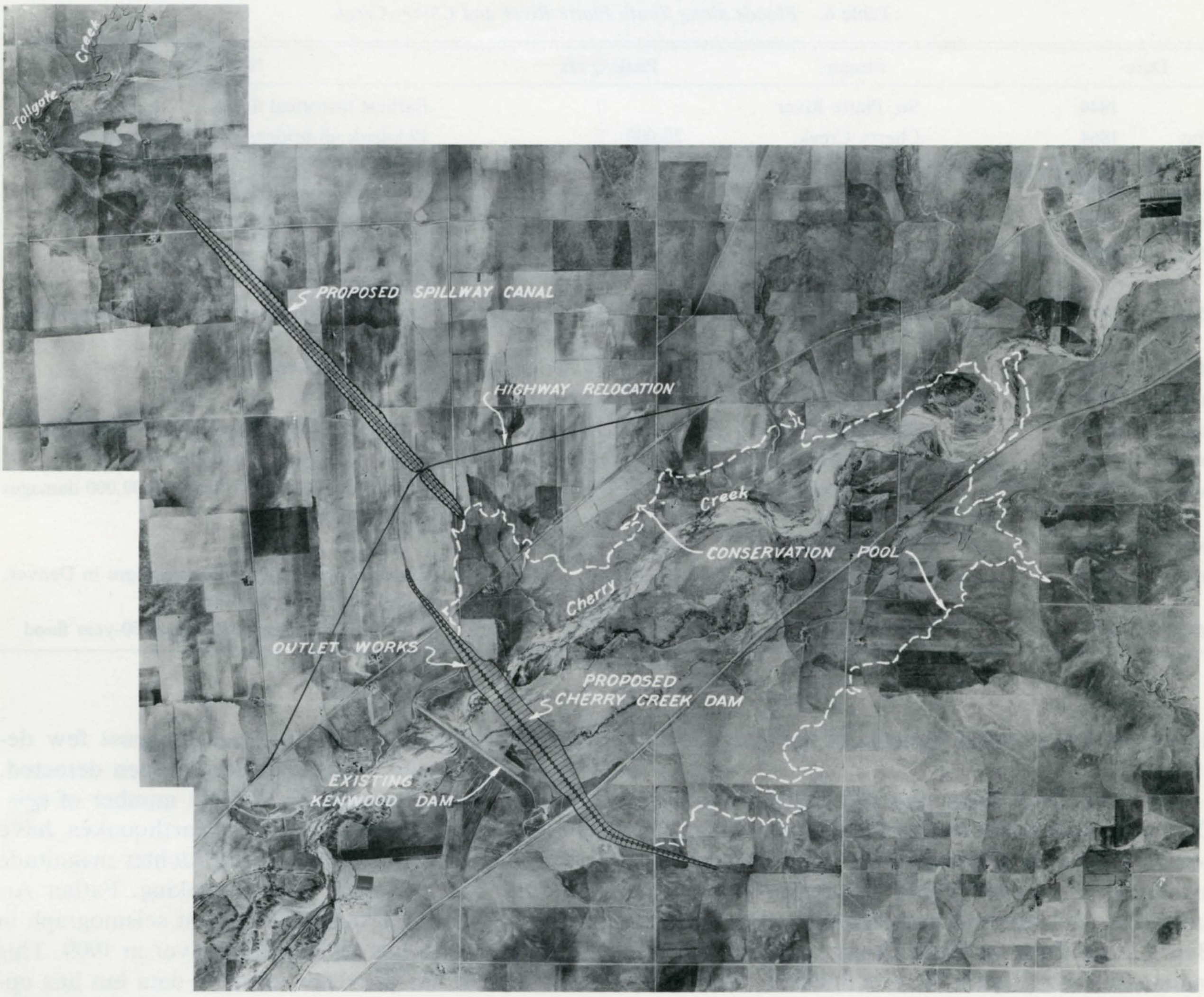


Figure 18. Vertical airphoto taken in the late 1940's showing the plan of the Cherry Creek Dam and Reservoir. Compare the size of the new dam with the then-existing Kenwood Dam. (Photo courtesy of U.S. Army Corps of Engineers.)

erated generally at low gain and is capable of detecting only large events. A seismograph was in operation at the University of Colorado at Boulder from 1954 to 1959. In December of 1961 the Colorado School of Mines installed a three-component seismograph at Bergen Park. This seismograph has operated at high gain since installation and is the primary source of instrumental data in Colorado. For a period during 1971 and 1972, the Colorado School of Mines and NOAA jointly operated a seven-station, state-wide network. One strong motion accelograph is currently operational in the Denver metropolitan area and is located in the Regency Inn (Figure 1).

Many earthquakes have been felt or instrumentally located in the Denver metropolitan area. Probably the largest of these events occurred on November 7, 1882 (Hadsell, 1968). It was felt throughout Colorado and in several adjacent states. Modified Mercalli Intensities of VII were reported in the Denver area. Most accounts of the earthquake suggest it was centered north of Denver, possibly near present-day Broomfield or Louisville. One recent evaluation suggests that the epicenter may have been in northwest Colorado, not in the Denver area (Dames and Moore, Inc., 1981). Although there were widespread, but scattered reports of violent ground shaking, relatively little property damage apparently resulted. This is probably due to the sparseness of development and prevailing earthquake-resistant one- or two-story frame construction of that time. A similar Intensity VII earthquake today could possibly result in millions of dollars of property damage, and perhaps loss of life.

In September of 1961, the U.S. Army drilled a 12,045-ft (3,671.3-m) injection well on the Rocky Mountain Arsenal property, and in March 1962 began to dispose of contaminated wastewater from its chemical manufacturing plant (Figure 1). Maximum injection pressures were 550 to 1,050 lbs/in.^{2} (379×10^4–724×10^4 N/m^2) with an injection rate of 200 to 300 gal/min (12.6–18.9 liters/s) (Evans, 1966). Beginning on April 24, 1962, and extending into 1968, Denver metropolitan area, which had not had a felt earthquake in 80 years, began to experience earthquakes at a rate of from 10 to over 100 per month. Most of the epicenters were within five mi (8 km) of the Arsenal well. Initially, the earthquakes were very small, and only a few were felt. The two largest earthquakes occurred on April 10, 1967 (Richter M = 5.0; I = VI), and August 9, 1967 (M = 5.3; I = VII). These quakes did considerable damage in the Commerce City and Northglenn suburbs north of Denver. In November 1965, D. M. Evans, a Denver-based consulting geologist, publicly expressed the view that the ongoing series of earthquakes were caused by the wastewater injection into the Rocky Mountain Arsenal well. His conclusion was based on the direct temporal correlation between the rate of fluid injection at the well and local earthquake frequency.

Because of increased awareness of the potential for damaging earthquakes and the possible relationships between the earthquakes and the disposal well, the U.S. Geological Survey, in cooperation with the Colorado School of Mines, was directed to evaluate the earthquake series. This study involved review of the pre-injection earthquake history of the area, and the establishment of a dense microearthquake detection network to accurately locate all events (Healy et al., 1966). No absolute evidence of any pre-injection seismic activity near the Rocky Mountain Arsenal was found, but two felt earthquakes were suspected of having occurred nearby. Sixty-two earthquakes were located by microearthquake monitoring during the Federal investigation that clustered in a seven-mi by two-mi (11 by 3 km) ellipsoidal zone that included the disposal well. This earthquake trend probably coincides with, and roughly defines, a zone of faulting or fracturing deep in the sub-surface (Kirkham and Rogers, 1981). The U.S. Geological Survey (Healy et al., 1966) concluded that there were definite temporal and spatial relationships between the disposal well and the series of earthquakes.

As a result of this postulated cause and effect relationship, fluid injection of the well was terminated on February 20, 1966. The earthquakes, however, continued to occur. The largest and most damaging earthquake, with a magnitude of 5.3, happened over a year after injection was halted. This apparent discrepancy was explained by Healy et al. (1968) using a conceptual fracturing model that suggests the larger earthquakes should occur after cessation of injection.

Most workers who have studied the Rocky Mountain Arsenal earthquakes believe that the fluid injection triggered the earthquakes (Healy et al., 1966, 1968; Hollister and Weimer, 1968). Considerable evidence has been introduced that indicates tectonic stresses existed in the area prior to injection and that the fluid injection triggered a partial release of this stored energy (Healy et al., 1968; Wyss and Molnar, 1972; Hsieh and Bredehoeft, 1979). The Denver earthquakes might have occurred even if the Arsenal well had not been drilled, and wastewater had not been pumped into the subsurface (Hollister and Weimer, 1968). This interpretation is supported by the recurrence of small-magnitude earthquakes in the northwest Denver suburbs of Thorton and Northglenn. On April 2, 1981 an earthquake of magnitude 4.1 occurred in this area and caused some minor damage. Thus, the possibility of future tectonic stress accumulation and release in the northeast Denver area cannot be ruled out at this time. The maximum magnitude of future earthquakes would probably be at least equal to the previous events (magnitudes 5.0 to 5.3) but could possibly be larger.

The entire State of Colorado is classified as "minor damage" in the seismic risk map of the United States (Algermissen, 1969). This classification implies the following seismic risk: "minor damage; distant earthquakes may cause damage to structures with fundamental periods greater than 1.0 second; corresponding to intensities V and VI on the Modified Mercalli Intensity Scale." Present building codes in Denver follow the Unified Building Code which adopts the risk map of Algermissen (1969) for seismic resistant design. Denver may, therefore, be facing a serious problem in the event of a moderate or major earthquake. Matthews (1973) argues this seismic rick classification is too

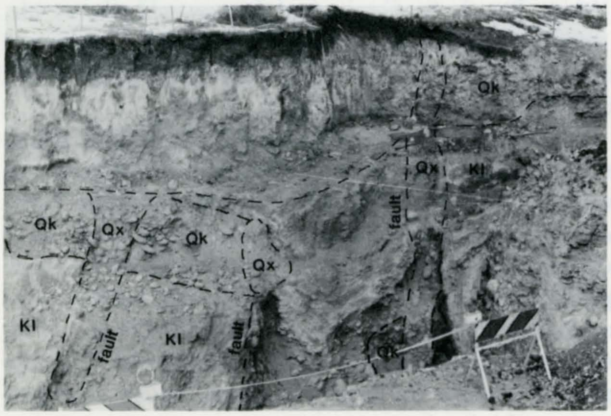


Figure 19. Photograph of east side of trench excavated across Golden Fault near Golden (Figure 1). Note faulted Kansan (?) deposits (Qk), especially the 18 ft (5.5 m) of offset along the far right fault. Zones of disoriented gravel clasts are labeled (Qx), and the Cretaceous Laramie Formation, (Kl) (generalized from Kirkham, 1977).

low for Denver because: (a) based on recent investigations of Cenozoic geology, the Rocky Mountains of Colorado should today be considered an active tectonic area; and (b) the 100-yr seismic history record in Colorado is too short to rule out a major or moderate earthquake in or near populated areas. Indeed, in 1967 (Intensity = VII) and perhaps 1882 (?) (Intensity = VII), earthquakes occurred in Denver with resulting intensities that exceeded the seismic design parameters specified in the city building code.

Alternative evaluations of seismic risk for Denver, based primarily on historic records, are: (a) Modified Mercalli Intensity VII or greater, and Richter magnitude 5.0 or greater, with a frequency of roughly four per 10 yrs, per square degree of surface area (Simon, 1972); and (b) horizontal acceleration of 0.04 g in rock with 10 percent probability of being exceeded in 50 yrs (Algermissen and Perkins, 1976).

Concern for the seismic safety of the Denver metropolitan area has resulted in several detailed studies of the Golden Fault west of Denver (Figures 3A and 3B). Scott (1970, p. C18) concluded that the Golden Fault could produce earthquakes having intensities greater than V. Recent excavations along the Golden Fault by the Colorado Geological Survey (Kirkham, 1977) indicated at least two periods of fault rupture with a total of 18 ft (5.5 m) of vertical displacement since the Yarmouth (?) interglacial. The most recent movement along the fault post-dates a layer of 600,000-yr old volcanic ash and overlying colluvium, but is believed to pre-date the surface soil of Sangamon (?) age (Kirkham, 1977) (Figures 1 and 19).

A major study recently completed concludes that the Golden Fault is not a capable fault and could not cause an earthquake strong enough to damage the Rocky Flats nuclear processing plant located along the fault trace northwest of Denver (Dames and Moore, Inc., 1981). Microearthquake monitoring of Chatfield and Bear Creek Reservoirs southwest of Denver has been conducted for the Corps of Engineers. No definite local earthquakes have been recorded (Patrick, 1977).

Earthquake insurance is generally available in Denver at rates of about \$0.44 per \$1,000 for frame structures, and \$0.68 per \$1,000 for all other buildings, with a 5 percent deductable.

ENVIRONMENTAL CONCERNS

Water Supply

The first water supplies for the City of Denver came from springs, shallow wells, and directly from Cherry Creek and the South Platte River. Addison Baker homesteaded 160 acres in 1866 around a large spring above the mouth of Cherry Creek. The spring had a daily output of 100,000 gal (378,500 l) and Baker delivered some of the water to residents of Auraria. This was Denver's first commercial water supply (Smiley, 1901).

In 1872 the Denver City Water Company piped water directly to houses from a large shallow well in Cherry Creek. Water was delivered through four mi (6.4 km) of wooden mains by a steam-driven pump. The rapid growth of population in the early history of Denver meant increasing demands on the water supply system; and for the next two decades, 11 private water companies competed to supply water from local rivers, ditches, and wells. One water company even provided free water to its customers for two years between 1889 and 1890 in an attempt to drive competitors out of business.

Some supply schemes included gates and ditches on the South Platte River about three mi (5 km) south of Denver to divert water to a lake from which it was pumped into mains beneath city streets. In 1887, infiltration galleries were constructed in the bed of Cherry Creek east of Denver. However, shallow wells and surface water supplies gradually became polluted.

The problem was temporarily solved in 1883. In March of 1883, R. R. McCormick was boring for coal near St. Luke's Hospital in north Denver. He

Figure 20. Cheesman Dam and Reservoir, a National Historic Civil Engineering Landmark. (Photo courtesy of the Denver Water Board.)

was forced to abandon the hole because a large flow of artesian water prevented further drilling. The ground water came from the Denver/Arapahoe aquifer underlying the Denver Basin at depths ranging up to 1,500 ft (457 m) and was of markedly purer quality than that delivered by the Denver City Water Company from the South Platte River (Cross et al., 1884). Other deep wells were soon drilled by brewers such as Zang and Tivoli, department stores such as Daniels and Fisher, and hotels such as the Brown Palace, as well as by private individuals. By 1900, more than 400 wells had tapped water-bearing zones in the buried aquifer at depths of 375 and 600 ft (114–183 m). Drilling costs were about $2 per ft (0.3 m) of depth (Cross et al., 1884).

Since the beginning of extensive use of the Denver/Arapahoe aquifer in 1883, the artesian head has declined under the city by approximately 400 ft (122 m) (U.S. Geological Survey, 1968). Extensive use is still made of ground water in Denver. The Brown Palace Hotel recently drilled a new well when its old one became sand-plugged. Ground water is still used by a private water company who delivers bottled artesian water. Water from wells is used in the laundry of a large hospital in Denver. The ground water is so soft it can be used successfully in boilers as well as kidney-treatment dialysis machines. Recently the hospital laundry had to double its soap consumption when using harder city water because the hospital well was shut down temporarily.

In 1894, the remaining water companies serving Denver merged to form the Denver Union Water Company, managed by W. S. Cheesman. The major contribution to Denver's water system by this private water company was the construction of Cheesman Dam and Reservoir on the South Platte River about 48 mi (77 km) southwest of Denver (Figure 20). Construction began in 1900 and was completed in 1905. The dam rises 222 ft (68 m) above the stream bed and is 1,100 ft (335 m) long including

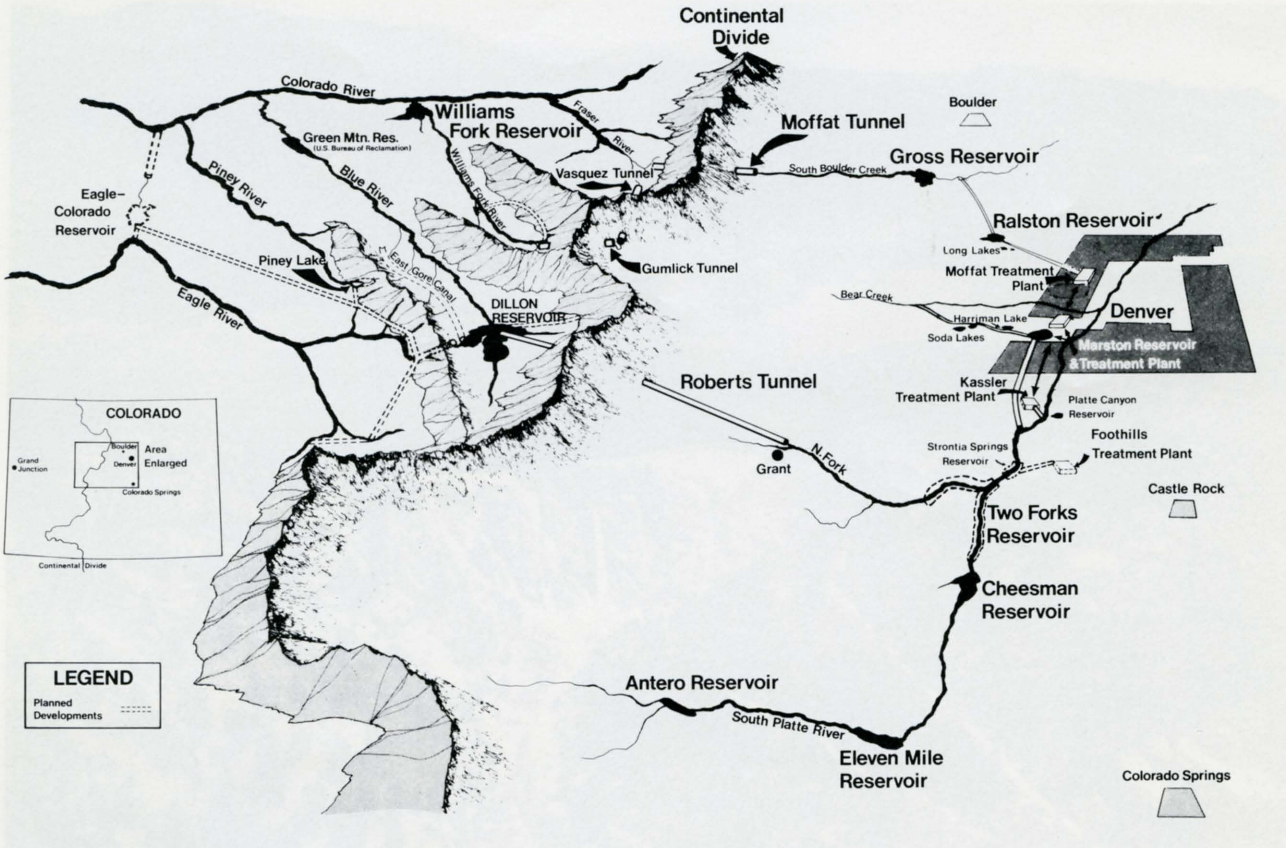


Figure 21. General plan of the Denver water supply system. (Diagram courtesy of the Denver Water Board.)

the spillway. The dam is constructed of locally-quarried granite blocks laid in cement mortar. Outlet works were tunneled into the rock abutting the dam, and water topping the spillway cascades over granite cliffs to the stream bed below. When completed in 1905, Cheesman Dam was the highest gravity-arch stone masonry dam in the world and provided the first substantial and continual on-stream storage of raw water for municipal use in the Rocky Mountain west. Cheesman Dam was designated a National Historic Civil Engineering Landmark by the American Society of Civil Engineers (ASCE) in 1973.

Denver's first significant water treatment facility consisted of underground infiltration galleries constructed in 1890 at Kassler, south of Chatfield Dam. The facility was rebuilt in 1906 and became the first plant west of the Mississippi River to employ the English slow-sand filter process. In 1979, it was designated a landmark by the American Water Works Association.

In 1918, Denver citizens voted to issue bonds for the purchase of the Denver Union Water Company. They also approved a management plan placing control of the system under an independent, non-political five-member Board of Water Commissioners appointed by the mayor for staggered six-year terms. The private water company was purchased for $14 million, which, in 1918, operated 613 mi (986 km) of conduits and water mains, a small pumping station and filter plant, and one storage reservoir on the South Platte River (Denver Water Department, 1976).

The Denver Water Board began buying water rights and acquired Antero Reservoir on the South Platte River in 1924 for $450,000. The following year, the Marston Treatment Plant was completed, and in 1932, Eleven Mile Canyon Dam, the third dam on the South Platte River, was built. This completed the initial development of the South Platte River as a water supply for Denver (Figure 21).

The Denver Water Board was a far-sighted organization. In 1922, the Colorado General Assembly passed the Moffat Tunnel Improvement District Bill to help construct a railroad tunnel through the Continental Divide and connect Denver with Salt

Table 8. *Major storage reservoirs and treatment plants, Denver water supply.*

	Capacity	% of Total	Completed	Dam Type
Reservoir				
Antero	15,878 a.f.	3.0	1909	Earth-fill
Cheesman	79,064	15.2	1905	Gravity arch masonry; with granite facing
Dillon	254,036	48.7	1963	Earth-fill
Eleven Mile	97,779	18.8	1932	Gravity arch concrete
Gross	41,811	8.3	1954	Gravity arch concrete
Marston	17,213	3.3	1902	Earth-fill
Ralston	11,272	2.1	1937	Earth-fill
(Strontia Springs)	(7,700)		(1982)	Thin arch concrete
Treatment Plant				
Kassler	50 mgd	9.6	1890; 1906	Slow sand filter
Marston	260 mgd	50.0	1925; 1961; 1967	Rapid sand filter, with micro strainers
Moffat	210 mgd	40.4	1937	Rapid sand filter, with micro strainers
(Foothills)	(125 mgd)	(19.4)	(1982)	Rapid sand filter

Lake City. The City of Denver got two features incorporated into the design of the tunnel: (a) it was to be constructed at 9,000 ft (2,743 m) rather than at a much higher altitude as favored by many transportation experts, and (b) the pioneer bore method of advance would be used to act as a service tunnel with cross-cuts drilled to the main bore. In 1928, when the railroad tunnel was completed, the Denver Water Board leased the pioneer bore, enlarged and lined it for the purpose of transmitting water from the Fraser River system on the western slope through the tunnel under the Continental Divide and into Denver (Figure 21). In June 1936, the first water flowed through the Moffat Tunnel to help alleviate the drought of the 1930's. In 1937, the Moffat Treatment Plant was completed to process this new water supply, and two reservoirs were constructed in 1937 and 1955 to provide storage (Figure 21). In 1979, the Moffat Tunnel was declared a National Historic Civil Engineering landmark by the American Society of Civil Engineers.

In 1946, another major transmountain diversion was begun with initial construction of a 23.3-mi-(37.5-km) long tunnel to transport water from the Blue River system on the western slope under the Continental Divide into the South Platte River. In 1956, six large construction companies won a joint-venture contract to finish the tunnel which they completed six years later. The Harold D. Roberts Tunnel, named after a Denver lawyer who secured many water rights for the city, was, when constructed, the longest underground water tunnel in the world (Wahlstrom, 1981). Dillon Dam and Reservoir were constructed between 1959 and 1963 to store western slope water for transport through the Roberts Tunnel. This reservoir doubled Denver's water storage (Table 8).

Colorado follows the Appropriation Doctrine of water rights; the purchase and transfer of these water rights, principally from agricultural to municipal use, is the way most domestic water supplies in Colorado have evolved (Cox, 1967). The City of Denver supplies water to several surrounding communities, and it was this ability to receive water that became the major incentive for annexation. But in 1951, prompted by impending water shortages, Denver defined an area surrounding the city outside of which water service would not be extended. This became known as the infamous "blue line," which forced the development of small, independent, and sometimes marginal, new water systems in the metropolitan area (Cox, 1967).

Total raw-water storage capacity of the Denver system in 1979 was 530,943 a-ft (655 hm), whereas total reservoir storage over the past five years has ranged from 58 to 89 percent of capacity (Denver Water Department, 1979). This captured water must be treated before distribution to customers, and therein lies the major problem of the Denver water supply.

During a two-week period in the summer of 1973, the city water treatment facilities were overtaxed on five days. In 1977, a mandatory water conservation program was begun because of inadequate treatment capacity and below-normal spring runoff. Since an estimated 40 percent of residential water is used for lawn watering, such watering is allowed only every third day during the summer. Water consumption in 1979 averaged 197 gallons per capita per day (gcd) (746 lcd), compared to an all-time high of 225 gcd (852 lcd) in 1974. The Denver Water Board also began a five-year tap allocation system whereby the number of new three-quarter inch water taps installed between 1977 and 1981 would not exceed 26,000. Denver Water Department customers comprise 40 percent of the state's population, yet account for only 1.3 percent of Colorado's water use. Agriculture is by far the largest consumer in the region.

A fourth water-treatment facility, the Foothills Complex, has been delayed five years because of environmental considerations. Construction finally began in 1979 and is scheduled for completion in 1982. The Foothills Complex includes a diversion dam in the South Platte Canyon at Strontia Springs, a connecting 3.4-mi (6.4 km) long tunnel to an initial 125 million gallons per day (mgd) treatment plant, and a conduit to bring the treated water to Denver. Ultimate treatment capacity is to be 500 mgd. The Foothills Complex will deliver water to the Denver metropolitan area by gravity flow and will also generate hydroelectric power (Figure 21).

In 1981, construction was also begun on a 1 mgd demonstration plant to recycle sewage effluent into potable water. Initially, none of the recycled water will be put into the city's water supply, although it will be made available for recreational and industrial uses.

The Denver water system is self-sustaining financially. No sales, property, or other tax dollars go into its operation. In 1980, water rates increased 29.3 percent for metered and flat-rate customers in Denver, 52 percent for residential users outside the city, and 50 percent for tap fees. About 37 percent of Denver City customers are metered. The remainder pay flat rates based on size of house, number of rooms, and number and kind of water-use devices. Annual water bills in Denver average $184.

Wastewater Disposal

The first sanitary sewer was constructed in downtown Denver in 1891. This same sewer is still the primary main to the Denver wastewater treatment plant downtown along the South Platte River. Between 1891 and 1936, wastewater from Denver was discharged, largely untreated, into rivers and streams. In 1936, the Denver Northside Wastewater Treatment Plant was completed as a primary treatment plant capable to treating 50 mgd (2.2 cms) (Figure 1). In subsequent years, the plant was expanded and modified and today can handle an average capacity flow of 106 mgd (4.6 cms) and a peak capacity flow of 160 mgd (7 cms). Average flows, however, have averaged 90 to 100 mgd (3.9 to 4.4 cms) and peak flows 135 to 140 mgd (5.9 to 6.1 cms). The Denver Northside Plant now handles 90 percent of Denver's wastewater flow, serving approximately 650,000 people. In 1979, the last remaining combined storm sewer/sanitary sewers were eliminated, giving Denver a completely separate wastewater system.

Primary treatment at the Denver Northside Plant consists of five mechanical processes. Five mechanically-cleaned, one-in. (25 mm) screens remove large solids arriving from the interceptors such as cans, papers, and debris. Heavy inorganic solids (grit) such as sand are removed, washed, and disposed of in landfills. The sewage is then pre-aerated by bubbling forced air through the liquid to reduce odors, bring grease to the surface, and help aggregate fine suspended solids. The liquid waste from the pre-aeration tanks is then transferred to settling basins where most of the suspended solids are removed. Each tank has a scraper to remove coarse solids from the tank bottom and a skimmer to remove floating grease from the surface. The liquid effluent is then transported by gravity flow in pipes to another plant for secondary treatment, and the solid sludge is pumped to digesters. There, anaerobic organisms decompose organics to more stable materials, producing methane gas which is used as an energy supply for the plant. Future plans at the Northside plant are to use sludge gas to operate 1,000-kw dual fuel, engine-driven generators that will eventually produce enough electricity to meet the entire plant's energy requirements. The primary treatment removes about 60 to 65 percent of the solids and about 30 percent of the incoming wastewater's biochemical oxygen demand (BOD).

Digested sludge is then pumped to another plant downstream for secondary treatment where it is processed and dried for ultimate disposal at the Lowry landfill east of the city (Figure 1). The long-range plan for sludge disposal is a land treatment facility in adjoining Adams County. However, this plan still requires permits and approval.

In 1966, the Metropolitan Denver Sewage Disposal District (MDSDD), consisting of 21 municipalities, of which Denver is the largest, completed the MDSDD No. 1 plant, a secondary wastewater treatment plant serving 1.1 million people in the metropolitan area (Figure 1). With the completion of this facility, Denver ceased discharging its effluent into the South Platte River and constructed an effluent pipeline to the MDSDD plant for secondary treatment.

About 10 percent of Denver's wastewater flows directly to the MDSDD plant, and the Denver Northside Treatment Plant has an overflow system which takes excess flows directly to the MDSDD No. 1 plant.

The secondary treatment consists of activated sludge with aeration using compressed air and pure oxygen and settling tanks. Incoming wastewater BOD averages 200 to 300 ppm, while discharged wastewater from the plant averages 20 ppm, representing 90 to 95 percent BOD removal. The plant handles 150 mgd (6.6 cms) average and has a capacity of 170 mgd (7.4 cms).

Processed, dried sludge from the plant averages 100 dry tons (91 tonnes) per day. Most all of this is hauled by truck to Denver's Lowry landfill 15 mi (24 km) east of the city for landfarming disposal (Figures 1 and 22), but small amounts go to the Colorado State University experiment station near Greeley, Colorado, for agricultural research, and to the Denver Parks system for fertilizer and soil conditioner. Sludge from this plant also was used by a mining company for reclamation of tailings from molybdenum mining in the mountains west of Denver.

Wastewater and sewage rates in Denver are based on water usage during the winter billing period (November to February) at $0.95 per 1,000 gal (3,758 l) of water usage, or $5.19 minimum, whichever is greater. For homes without water meters, flat rates are assessed based upon house size, number of rooms, and number of water-use devices.

Solid Waste Disposal

In 1980, the City and County of Denver operated no sanitary landfills, and no solid wastes were disposed within the city limits of Denver. The city collects household rubbish and other waste materials, hauls them to landfills surrounding the city, and pays tipping fees. This has not always been the case in the past. Much high-value real estate in the City of Denver has been developed over old landfills within the city limits, including major shopping centers, municipal facilities, warehouses, light industries, sports arenas, parks, and residential structures (Figure 14). These former landfills are concentrated along the valleys of the South Platte River and Cherry Creek (McBroome and Hansen, 1978). The City and County of Denver still owns a landfill on the Lowry Bombing Range east of the city in adjacent Arapahoe County, but the landfill is operated by a private contractor.

Table 9. *Solid waste disposal in Denver, 1979.*

Location of Landfill (Figure 1)	Amount (Tons) of Waste	Percent of Total
Property Investment Sanitary landfill, Adams Co.	77,077	40
Arapahoe Co. Sanitary landfill	77,077	40
Rooney Road Sanitary landfill, Jefferson Co.	19,269	10
Lowry Bombing Range landfill, Arapahoe Co.	19,269	10

In 1979, Denver collected 192,693 tons (174,811 tonnes) of household rubbish from 142,000 homes. Rubbish collected averages 400 tons (363 tonnes) per day in winter and 800 to 900 tons (726–816 tonnes) per day in summer. Assuming 2.4 people per home, that means 340,800 people were served; and residents generated an average 3.1 lbs (1.4 kg) per person per day. The City of Denver spent about $9 million on waste disposal in 1979, which amounts to about $26.40 per person served per year.

Denver utilized four sanitary landfills for disposal of household rubbish in 1979 (Table 9) (Figure 1). Three of these landfills are nearly full now, so in the next five years Denver will face a major shift in the location of its solid waste disposal to the enormous Lowry landfill. This site was formerly a practice bombing range for pilots in training at Lowry Air Force Base during World War II. Denver bought the land from the Federal government after the war. This landfill is 2,800 a (11.3 km^2) and has a projected life of 100 years. However, shifting waste disposal exclusively to this landfill would mean an additional 100,000 mi (160,900 km) per yr hauling for Denver.

Feasibility studies have been completed for the design of an incineration plant closer to the city capable of burning 300 tons (272 tonnes) per day of solid waste. The plant would generate steam to be sold to a utility company, to be used in generation of electricity.

In the Denver metropolitan area, 80 percent of the solid wastes now being generated is estimated to consist of organic materials (Ralph M. Parsons Company, 1976, pp. 2–26). The hazards of methane gas produced in landfills has been discussed earlier, but in Adams County, which adjoins Denver on the north, gas is being considered a resource rather than a hazard. The county received a U.S. Department of Energy grant to investigate methane recovery feasibility in seven old landfills. The studies have shown that five of the seven landfills are potentially good sites for recovery and profitable use of methane gas (SCS Engineers, Inc., 1980). At two sites, gas is actively being ventilated to the atmosphere today. These five landfills contain an estimated 9.85 million tons of solid waste, which is capable of producing 0.15 ft^3 (0.004 m^3) of gas per pound per yr which is 45 to 50 percent methane. A total volume of three ft^3 (0.08 m^3) of gas can be recovered from each lb (0.45 kg) of waste, which indicates gas could produce $1,400 \times 10^6$ ft^3 (40×10^6 m^3) of methane per yr, containing 450 to 500 BTU per ft^3 (compared to 850 to 1,000 BTU per ft^3 for natural gas). This is enough energy to heat about 3,500 homes in Denver for a year. Colorado House Bill No. 1214 was subsequently passed by the State Legislature in April 1980, giving counties and municipalities power to explore, develop, produce, distribute, market, and finance landfill-generated methane gas.

Hazardous Wastes

There are approximately 333,000 tons (302,098 tonnes) of hazardous wastes produced in the Denver metropolitan area each year (Hynes and Sutton, 1980). This is about 40 percent of the state's total hazardous-waste production. These wastes include acidic and brine solutions, heavy metal and oil sludges, contaminated wastewater, and solvents.

Since 1942, the Army Chemical Corps has operated a chemical manufacturing plant at the Rocky Mountain Arsenal just north of Denver (Figure 1). Between 1942 and 1957, contaminated wastewater from the Arsenal was contained in shallow evaporation ponds constructed in the permeable eolian surficial deposits underlying the Arsenal property. No attempt was made to seal these ponds. The result was severe pollution of the local shallow ground water. In 1957, the lagoons were sealed with asphalt, but this was not completely successful. Maximum migration rate of the wastewater was approximately three ft (1 m) per day. By 1960, an area of six and one-half mi^2 (16.8 km^2) extending to the northwest from the Arsenal to the South Platte River had been contaminated by chlorates and 2,4-D type compounds, both of which are effective herbicides. This resulted in extensive crop damage (Walker, 1961; Lindvall, 1979a, 1980).

Since December 1980, the Lowry landfill, owned by the City and County of Denver but operated by a private contractor, is the only approved site for disposing of non-radioactive hazardous wastes. More than 200 firms from the Denver area dump such wastes there.

The site is underlain by eolian sand, loess, alluvium, and Denver/Dawson mudstones and sandstones. Sewage sludge is either spread on the ground and plowed into the soil, or buried in bulk (Figure 22). Land disposal of sludge began in 1969, and by 1976, application rates ranged from 60 to 210 dry tons (54–191 tonnes) per acre (Robson, 1977). Liquid wastes were discharged into unlined earth trenches until several million gallons of liquid accumulated. The trenches were then filled with refuse and covered with a layer of earth (Robson, 1977).

By 1976, shallow stock-watering wells around the landfill were found to have markedly degraded water quality (Robson, 1977). The regional Fox Hills aquifer lies at a depth of about 1,800 ft (600 m) below the site and will not be affected by the disposal. The Colorado Geological Survey has subsequently classified the site as only marginally suitable for disposal for non-nuclear hazardous industrial wastes (Hynes and Sutton, 1980, plate I).

The Shell Chemical Company, a leased tenant of portions of the Rocky Mountain Arsenal, recently spent $1.6 million for the construction of three clay-soil-lined evaporation ponds, covering 22 a (8.9 ha) adjacent to the Lowry landfill (Camp Dresser and McKee, Inc., 1978). The ponds were completed in 1980. An additional hazardous waste facility, incorporating storage cells for drummed waste, was under construction by a private operator in 1981.

The disposal of hazardous wastes in the Denver metropolitan area is presently in a state of turmoil. In 1968, Denver obtained its landfill designation certificate from Arapahoe County when there were no legal distinctions between solid and liquid, or hazardous and special wastes. In early December 1980, the Arapahoe County Commissioners passed a resolution giving Denver 10 days to stop the dumping of hazardous chemical and toxic wastes at the Lowry landfill. From then until 1980, there was a rising tide of public objection from residents in the vicinity. A court injuction now has temporarily halted the resolution of the County Commissioners. This

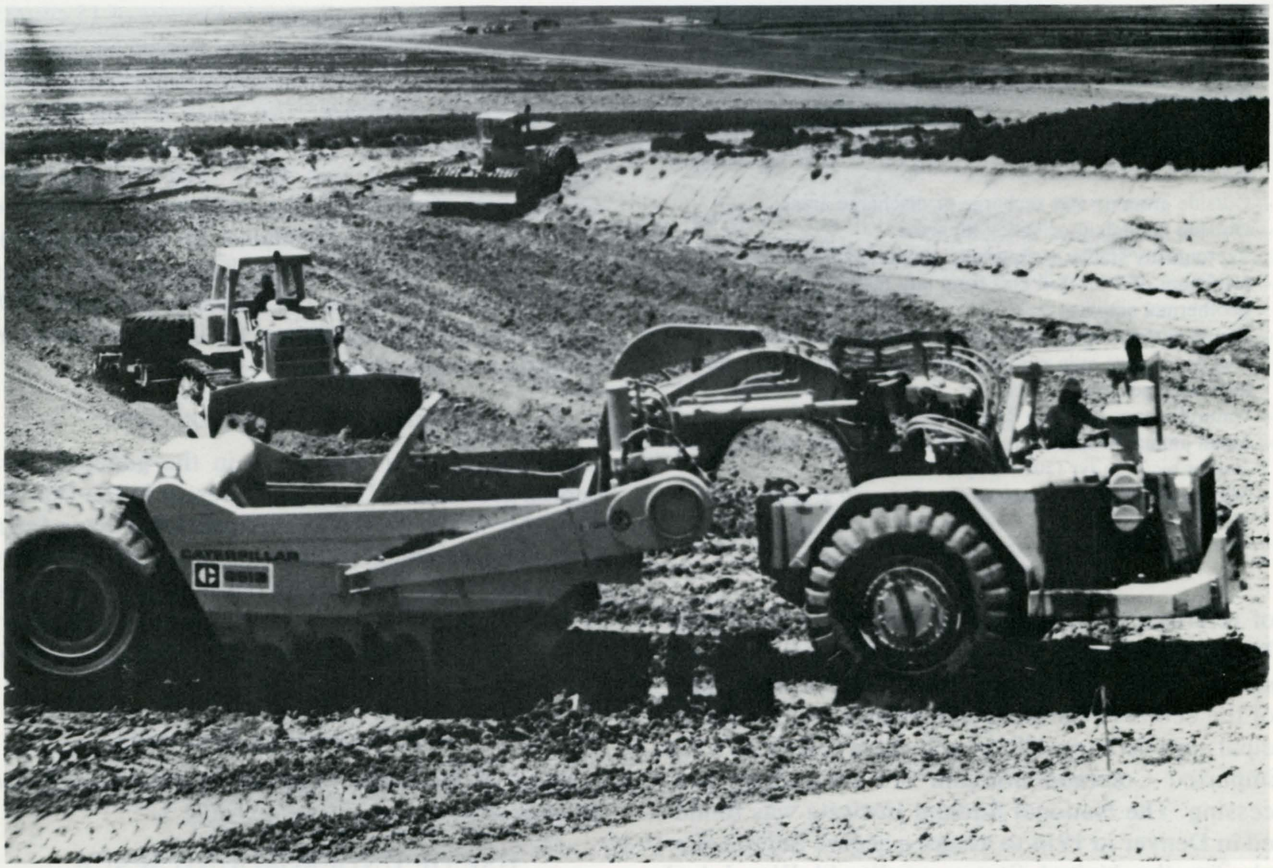


Figure 22. Construction underway at the 22 a (8.9 h), industrial brine evaporation pond facility of the City-County of Denver. The scraper pan in the foreground is transporting selected "suitable" materials from grading of an adjacent pond, to placement in a 6 in. (15 cm) lift for compaction-placement as bottom-liner fill. The facility is constructed entirely of silt and clay-size materials from the undifferentiated Denver/Dawson Formations, as encountered in site grading. Pond layout took into consideration stratigraphic and facies variations encountered in exploration and verified during construction. Laboratory determinations of the coefficient of hydraulic conductivity (permeability) of the engineered bottom-liner and key-trench cutoff fill indicated achievement of values less than 10^{-9} cm/sec at 95 percent of maximum dry density. The fill is being compacted by the sheepsfoot roller and scarified between lifts by the dozer, as shown in this view, taken in August of 1979 (Photograph by Allen W. Hatheway).

is a difficult situation, because there is no immediate alternative disposal facility in the entire state. North of Denver in Adams County, a site has been approved by the Environmental Protection Agency and the Colorado Department of Health, for hazardous waste disposal, but the site does not as yet have county approval and may not receive it.

The resolution passed by the Arapahoe County Commissioners also ordered the Metropolitan Denver Sewage Disposal District to halt dumping and spreading of sludge from its South Platte River plant by December 31, 1982. Local officials fear that the closing of the Lowry landfill to the dumping of hazardous wastes, without a nearby alternative, could precipitate a rash of "midnight dumping" of hazardous materials. Task forces presently are meeting to consider establishing a new operation with optimal geologic conditions within a reasonable distance of the Denver metropolitan area. Criteria set by the Colorado Geological Survey are shown in Table 10. Optimal conditions for potential storage of hazardous wastes near Denver are found in the upper and lower members of the Pierre Shale (Hynes and Sutton, 1980).

Radioactive Spoils

In February, 1979, the Environmental Protection Agency notified the Colorado Department of Health

Table 10. *Siting considerations for hazardous waste disposal in Colorado (from Hynes and Sutton, 1980).*

—Absolute containment for at least 1,000 years
—Minimum vertical thickness of 150 ft (46 m) of shale or clay with in-place permeability no greater than 0.1 ft/yr (30 mm/yr)
—Outside groundwater recharge or discharge areas
—Outside floodplain or valley-fill areas
—Tectonically stable; structurally simple, geologically
—Minimum of 1 mi (1.6 km) from any major fault, igneous, or geothermal activity
—Stable surface, not subject to erosion greater than 0.5 acre-feet per square mile per year (238 cubic meters per square kilometer per year
—Natural slopes between 2 and 5 percent
—Mean annual evaporation should exceed mean annual precipitation by 20 in./yr (508 mm/yr)
—Maximum 24-hour rainstorm should be no greater than 6 in. (152 mm)

of references found in three early U.S. Bureau of Mines Bulletins to a former "National Radium Institute" in Denver (Parsons et al., 1915). At the turn of the century, Germany and France were the principal suppliers of radium, and these countries even imported Colorado uranium ore for radium processing. The National Radium Institute was founded in Denver in 1914 to assure a secure radium supply for the United States, as World War I had begun. Radium had an alleged medical value for cancer treatments.

Over 10,000 tons (9,072 tonnes) of high-grade uranium ore (2.5 percent) were milled at the National Radium Institute's facilities between 1914 and 1917. In radium refining, uranium oxide was considered a waste product which, subsequently, was disposed of as artificial fill and construction material in the Denver area. Since the isotopes involved have half-lives of thousands of years, 60 years of dormancy has not greatly reduced the natural radioactivity.

Investigations in old telephone directories revealed that the former location of the National Radium Institute is the present site of a major privately-owned brick and tile storage and distribution facility in south Denver (Figure 1). With the cooperation of the owner, the State Department of Health visited the site and measured soil radioactivity of 1,600 microRoentgens per hour (Colorado Department of Health, 1981).

Further investigations identified 32 contaminated sites in Denver with maximum gamma intensities as high as 15,000 counts per second compared to natural background radiation in Denver of 15 counts per second. These sites include a restaurant parking lot, vacant lots, industrial and commercial property, and street subbases. The State Health Department has conducted drilling and soil sampling at nine sites, and estimates that a total of 35,000 yds^3 (26,775 m^3) of contaminated soil exists at these locations (Colorado Department of Health, 1981). The Denver radium-bearing contamination sites have been included in the recently passed (1980) federal superfund legislation to cover the costs of hazardous-waste clean-up.

Wetlands and Shore Protection

No wetlands or shorelines in the generally accepted geotechnical sense are present in the Denver area. Most low or poorly drained areas have been artificially dammed to raise the level of the many small reservoirs that exist in the area. Shore erosion is not a problem for such ponds, nor along the margins of the large flood-control reservoirs near Denver.

Major Engineering Structures

Some of the major engineering structures in the Denver area are tabulated in Table 5.

USE OF UNDERGROUND SPACE

There is only one significant use of underground space in the Denver metropolitan area, the storage of natural gas in old underground coal mines by the Public Service Company of Colorado.

In the early 1950's, the Public Service Company of Colorado, serving the Denver area, was faced with the need to store natural gas for peak-usage during the winter. After studying 16 storage sites, the utility company selected the old Leyden No. 3 coal mine located about 12 mi (19 km) northwest of Denver (Figure 1). Sub-bituminous coal occurs in the lower 200 ft (61 m) of the Laramie Formation at a depth of 700 to 1,000 ft (213–305 m) below the ground surface. Mining began in 1903, and coal mined from the Leyden mines was used primarily by the Denver Tramway Company for electrical power generation for trolley cars in Denver. Trolley service connected the mine to the city where coal was hauled in coal cars to electric-generating plants. The Leyden mine closed in 1950 after six million tons (5.4 million tonnes) of coal were mined, resulting in a void space of 150 million ft^3 (4.3 million m^3) (Meddles, 1978; Brown, 1978).

The Leyden mine was selected for underground storage of natural gas for several reasons. The mine was close to the Denver market, had adequate storage capacity, large volumes of gas could be withdrawn from a few wells, could be recharged quickly during off-peak demand times, and was located in a sparsely inhabited farming and ranching area (Figure 1).

After extensive testing indicated that the enclosing shale provided an impervious storage area, development of the mine as a gas storage facility began in 1959. By late 1961, natural gas was being stored successfully in the mine and continues to be so stored 20 years later. Storage capacity is presently 1.6 billion ft^3 (BCF) of gas with a maximum withdrawal of 185 MCF per day (Meddles, 1978). By being able to rapidly recycle the storage volume several times during a heating season, the utility company has been able to maintain the storage capacity needed for large peak-day deliveries.

Other minor uses of underground space in the Denver area include access tunnels and excavations for commercial space under some of the older large buildings in the downtown area (Price, 1982), and the Foothills Tunnel for the transmission of water from the Stronita Springs diversion dam in the South Platte River Canyon to a treatment plant east of Roxborough Park (Table 5).

ENGINEERING GEOLOGIC PRACTICE IN DENVER

The need for engineering geology appeared early in the history of Denver. Precious metals mining and subsequent railroad and highway construction into and from the Denver area, which served as a trade, transportation, and processing center, necessitated technical analyses of mining engineering and route feasibility. The aridity of the Denver area also required extensive irrigation and water-supply engineering early in its history, to serve agricultural and domestic water needs.

The need and demand for engineering geology in the Denver area has continued to expand in proportion to the rapid economic and social growth of the region. The first legislation (Shelton and Prouty, 1979) with significant impact on the practice of engineering geology in Colorado was Senate Bill 35, passed in 1972, which dealt with land subdivisions. The bill requires reports on the geologic characteristics significantly affecting the proposed land use for all new subdivisions in unincorporated areas of the state. A *subdivision* of land is defined in the law as any division of land into parcels of 35 a (14.2 ha) or less. Since enactment of Senate Bill 35, most geologic reports required by the law have been prepared by engineering-geologic consultants for private subdivisions and/or land developers. Reports are required to be submitted to county planning departments which, in turn, submit them to the Colorado Geological Survey for review and comment. Approval or disapproval of a subdivision is a county-government decision. The State Geological Survey has no regulatory authority over a county-government decision based on the geologic report.

House Bill 1574, passed in 1974, requires that all geologic reports prepared for governmental review must be prepared by a professional geologist. A professional geologist is currently defined as an individual with at least 30 semester hours of geological education and five years of experience.

Two attempts have been made to enact a geologist-registration law in Colorado; both have been unsuccessful. The first attempt, in 1973, provided for registration of both geologists and geophysicists, and each class would have been examined separately. A "grandfather clause" and reciprocity with other states was included with this legislation. The second registration bill, introduced in the 1976 legislative session, was restricted to the registration of engineering geologists. The provisions of this bill were otherwise similar to the first. By limiting the registration requirement to engineering geologists, it was felt by the proponents of this bill that it would stand a better chance of passage, as much of the opposition to the first bill came from outside the engineering-geology profession. Today geologists may register as "Professional Engineers," but this requires an undergraduate engineering education and successful completion of "Engineer-in-training," and "Professional Engineer" examinations.

House Bill 1041, passed in 1974, requires the Colorado Geological Survey to assist local governments in identifying and designating geologically hazardous areas subject to avalanches, landslides, rockfalls, mud and debris flows, unstable slopes, seismicity, radioactivity, ground subsidence, expansive soils and rock, and mineral resource areas. The Colorado Geological Survey also helps adopt guidelines for the administration of these special state interest areas (Rogers et al., 1974).

Two other pieces of recent legislation have had a significant impact on the practice of engineering geology in the Denver area and Colorado. House Bill 1529 (the "Sand and Gravel Bill"), passed in 1973, precludes any governmental body in the state from zoning for alternate uses any area of mineral deposits deemed to have significant economic or strategic value. The law applies to any city and/or county having a population of 65,000 or more, and requires local governments to adopt a master plan for the extraction of commercial mineral deposits. However, no penalties are assessed for failure to comply with the master plan requirement. Most of the emphasis of House Bill 1529 is directed toward production of aggregate and long-range plans for their extraction in the populous (high demand markets) counties of the state. Denver City and County prepared an extraction plan in accordance with the law, but was exempted by the state because of the small area involved.

A companion bill, House Bill 1065, passed in 1973 (Colorado Mined Land Reclamation Act), established a mined land reclamation board with a mandate to ensure proper reclamation of mined-out areas in the state. The result of legislation passed since 1972 is that engineering geology is in great demand in the Denver metropolitan area, and will continue to experience great demands in the future. Between 1970 and 1980 the population of the metropolitan area increased by 30 percent, and housing units by 57 percent. The Denver Regional Council of Governments predicts that the population of the metropolitan area will increase to 2.4 million by the year 2000.

Although the City and County of Denver does not have a city geologist, several adjacent suburbs and counties do have geologists or planners with geology backgrounds on their staffs. Sand and gravel, crushed-rock aggregate, and clay products companies in Denver employ engineering geologists for exploration, development, and reclamation. Private consulting companies are also busy preparing subdivision reports, reclamation plans, hazard assessments, and geotechnical designs for the continued rapid growth of the Denver metropolitan area.

ADDITIONAL INFORMATION

For those people who are interested in seeing some of the engineering geology conditions and situations described in this report, several published field trip logs for the Denver area exist. The references can be found in the bibliography under Weimer and Haun, 1960; Conference Field Trip Committee, 1969; Hansen et al., 1976; and Kirkham, 1981.

ACKNOWLEDGEMENTS

Any paper covering a topic as broad as the geology of Denver must of necessity be a compilation, drawing on the work of many people too numerous to mention individually. The bibliography and citations in the text hopefully have accurately credited the work of these scientists and engineers. Much of this report is based on work done by the U.S. Geological Survey and the Colorado Geological Survey. We would like to thank Ralph R. Shroba, Wallace R. Hansen, Michael W. West, Willard G. Owens, Richard C. Hepworth, Ralph Mock, Robert M. Kirkham, and Fu Hua Chen for their review and comments on an early draft of the manuscript, and James M. Soule for help in writing the sections on engineering geology practice in Denver. We would like to extend a special note of grateful thanks to Howard E. Simpson for his exhaustive review and knowledgeable insights about Denver area engineering geology. The paper was markedly improved by his generous help. Allen W. Hatheway, the Series Editor, proved to be a patient, supportive, and informative colleague and reviewer. It has been a genuine pleasure working with him. Christopher C. Mathewson, AEG *Bulletin* editor, competently and thoroughly reviewed the final draft of the paper, and corrected many of our oversights and omissions. This was a difficult task for a manuscript of this length, and we thank him for his help. Finally, a grant from the Graduate School of the College of Arts and Sciences, University of Denver, covered typing and some cartography expenses.

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