Environmental Geology of the Front Range Urban Corridor and Vicinity, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1230

Environmental Geology of the Front Range Urban Corridor and Vicinity, Colorado

By WALLACE R. HANSEN *and* ELEANOR J. CROSBY

With a section on PHYSICAL PROPERTIES *and* PERFORMANCE CHARACTERISTICS OF SURFICIAL DEPOSITS *and* ROCK UNITS in the GREATER DENVER AREA *By* RALPH R. SHROBA

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A descriptive summary of geologic conditions in a region of varied physiography and rapid urbanization

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METRIC CONVERSION FACTORS

Multiply metric units	By	To obtain U.S. customary units
millimeter (mm)	0.0394	inch (in)
centimeter (cm)	0.3937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.621	mile (mi)
square kilometer (km^2)	0.386	square mile (mi^2)
cubic meter (m^3)	35.311	cubic foot (ft^3)
ton (t)	1.1023	ton (U.S. short)
milligram per liter (mg/1)	1	part per million (ppm)
kilogram per cubic meter (kg/m^3)	0.06243	pound per cubic foot (lb/ft^3)
millimeter per hour (mm/h)	0.0394	inch per hour (in/h)
liter per minute (1/min)	0.26418	gallon per minute (gal/min)
kilonewton per square meter (kN/m^2)	20.8333	pound per square foot (lb/ft^2)
joule	0.00095	British thermal unit (Btu)
radian (rad)	57.31	degree

ENVIRONMENTAL GEOLOGY OF THE FRONT RANGE URBAN CORRIDOR AND VICINITY, COLORADO

By WALLACE R. HANSEN and ELEANOR J. CROSBY

ABSTRACT

Some geologic processes in the Front Range Urban Corridor have resulted from human activities; others are quite natural but have been enhanced artificially. Environmental stress intensifies when land development involves easily disturbed sediments such as loess, eolian sand, organic loam, and expansive clay. Adverse environmental impacts can sometimes be mitigated if geologic knowledge is applied to the solution of land-use problems.

The Front Range Urban Corridor, centered on Denver, straddles the boundary between the Front Range of the Southern Rocky Mountains and the Colorado Piedmont section of the Great Plains. This boundary is defined by a zone of sharp-crested foothills or hogbacks. The mountains are underlain by a crystalline complex of Precambrian igneous and metamorphic rocks, some as old as 1.75 b.y. (billion years). The hogbacks and piedmont are underlain by sedimentary rocks ranging in age from Cambrian to Holocene; about 25 different major rocks formations and many surficial units are recognized. Physical properties vary widely from unit to unit. Although the piedmont is more subdued topographically than the mountains, it has varied relief and form.

For this report, the long geologic history of the area is divisible into eight time intervals of unequal length. The longest interval, Precambrian time, is further broken by plutonic events 1.75-1.70 b.y. ago, 1.45-1.39 b.y. ago, and 1.04-0.98 b.y. ago. Orogeny accompanied the first and second events. Three ensuing intervals of relative crustal stability were each followed by orogeny, in Pennsylvanian, Late Cretaceous, and Miocene time. In and after Miocene time, faulting, uplift, erosion, and deposition led to the elevation of the present Front Range and the shaping of the mountains and piedmont.

Two major features dominate the geologic structure of the Front Range Urban Corridor—the Front Range uplift on the west and the Denver Basin on the east. These features are regional in size and extend far beyond the limits of the corridor. The Front Range is a broad, flat-topped anticline, but erosion has removed the sedimentary cover from the crustal part of the fold, and the internal structure of the Precambrain core is very complex. The boundary zone between the uplift and the Denver Basin is a steep monocline along which the sedimentary rocks are tilted, faulted, and, locally, folded into subordinate anticlines.

The Colorado part of the Denver Basin is broadly asymmetrical, having its axis much closer to the west border of the basin than to the east. At the deepest part of the basin, Precambrian rocks are more than 2,300 m below sea level. The general simplicity of the basin is modified by subordinate folds and faults, especially in the northern part.

Urban mineral resources are extracted from within the Front Range Urban Corridor for local use. These primarily industrial products include gravel, sand, crushed stone, riprap, clay, dimension stone, limestone, and earth fill. Other products extracted, but not necessarily for local use, include coal, natural gas, and petroleum. To be competitive, urban mineral resources must be obtained close at hand, often within metropolitan areas. Urban growth, which creates the demand and consumes the products, sometimes curtails production by preempting the unextracted resources for other land uses.

Extensive deposits of gravel, sand, sandstone, fine-grained igneous rock, clay, and expandable shale underlie the Colorado Piedmont. The Hogback belt yields clay, limestone, dimension stone, crushed rock, landscaping rock, and gypsum. The mountain area is a source of crushed rock, riprap, gravel, sand, earth-fill material, and weathered granite (grus). Most high-quality gravel is extracted from beneath the flood plains or adjacent low terraces of the major streams. Less sought-after gravels cap higher terraces and pediments.

Most urban mineral extraction leads to the excavation of open pits, and what happens to the pits after extraction is completed has long-term significance to the community. In 1973 the Colorado Legislature enacted into law a bonded reclamation plan for such mined areas. Some pits have been backfilled with urban refuse and reclaimed as valuable real estate; to the extent that such a pit can be rehabilitated for other use, it is a community asset rather than a liability. Problems that result from solid-waste disposal in landfills, such as ground subsidence, noxious gas generation, and groundwater pollution, can be minimized by engineered design. Alternatively, exhausted pits can be converted to urban lakes and open space.

Coal of Late Cretaceous and Paleocene age underlies parts of all counties in the Front Range Urban Corridor. Little if any coal is now being mined, but a resumption of mining in the future seems likely. Most remaining Cretaceous subbituminous coal is too deep to be removed by surface mining, but a huge resource of strippable Paleocene lignite is in the Denver Formation just east of Denver. Individual beds of strippable lignite as much as 8 m thick lie generally less than 60 m below the surface. Past underground mining of subbituminous coal at shallow depths in the Boulder-Weld and Colorado Springs coal fields has caused ground subsidence which could present problems to subsequent land use.

The Denver Basin is one of the leading oil-and gas-producing areas of the Rocky Mountain States. By far the largest gas field in the basin is Wattenberg, which lies mostly in the Front Range Urban Corridor between Denver and Greeley and has the highest estimated ultimate gas productivity in Colorado. Oil has been produced in the Denver Basin chiefly from areas east of the corridor, but many wells inside the corridor are very productive. The most productive reservoir rock, for both oil and gas, is the "J" sandstone member of the South Platte Formation of the Dakota Group.

Various kinds of soil problems, particularly with respect to highways and lightly loaded buildings, increase costs of preventive or precautionary construction and damage repair. Foremost are problems caused by expansive soils, which may create swell pressures exceeding 15 metric tons per square meter. Other problems are related to eolian soils, soils rich in organic matter, and residual or transported mountain soils. Mass wasting is closely related to soil problems, although it commonly involves bedrock also. Urbanization is spreading into areas where mass wasting is likely but can be minimized by care in site selection and treatment.

Urbanization has affected and been affected by the hydrology of the Front Range Urban Corridor. Urbanization has altered stream flows, the frequency and magnitude of floods, channel characteristics, scour and sedimentation, ground-water conditions, and water quality. Episodic flooding is perhaps the foremost natural hazard in the area, on the plains as well as in the mountains. Flooding is characterized by uncommonly high velocities and short durations. The seasonal distribution is distinctly bimodal—May through September—with peaks in the first week of June and the first week of August. Astonishing precipitation rates have accompanied some storms, the maximum recorded being 610 mm (millimeters) in one day, mostly in about 3 hours on May 30, 1935, at Elbert. Much ground water is available for use in the Front Range Urban Corridor in valley-fill alluvium, pediment deposits, terrace deposits, eolian sand, and bedrock. Bedrock aquifers contain vast quantities of ground water suitable for many purposes; the principal aquifers are in formations such as the Laramie, Fox Hills, Arapahoe, and Dawson Formations, but many mountain households obtain water from fractures in the Precambrian bedrock.

For a semiarid region, the Front Range Urban Corridor contains a surprising number of small lakes. Many are natural water bodies that have been enlarged by damming. Most are irrigation reservoirs, but with increasing urbanization, uses are changing. As centers of real-estate development and water-related recreation, lakes enhance the value of adjacent property.

The swarm of earthquakes that followed the injection of waste water into the deep disposal well at the Rocky Mountain Arsenal caused concern about possible seismic hazards in the area. Except for those tremors, however, few earthquakes larger than MM (modified Mercalli intensity) III have been experienced in the Front Range Urban Corridor in 100 years. Because no fault offset has been found in deposits younger than Sangamon(?) age (125,000 years ago), the frequency of earthquakes strong enough to cause ground breakage has been very low.

INTRODUCTION

Since the late 1960's there has been a growing nationwide awareness of the importance of geologic and hydrologic information to the design and implementation of plans for urban land use. More than ever before people now realize the part that the earth sciences play in their daily lives. Nowhere, perhaps, has this awareness grown faster than in the urbanizing areas along the east slope of the Front Range in Colorado, centered on Denver and spread north to south from Fort Collins and Greeley to Colorado Springs. An alert technical community in the universities, engineering firms, businesses, and governmental agencies and a knowledgeable citizenry have been supported by legislative actions intended to assure that geologic and hydrologic factors are considered in land-use planning and development. Laws enacted by the State Legislature have addressed ground conditions as related to land development, open-pit extraction of gravel, sand, coal, limestone, and other commercial mineral deposits in populous counties, reclamation of mined lands, and land development in areas of geologic hazard.

Progress has been made, but more work is needed. The flood plain concept is still widely misunderstood. Buildings are still being damaged by expansive soils. Urban growth is still encroaching on mineral resources and wildlife habitats. Nonrenewable resources that could be recycled are still being discarded. High concentrations of pollutants still enter the biosphere.

Environmental stress focuses on the urban setting. It increases when human activity alters the biosphere, as in the urban setting where most human activity is concentrated. For countless centuries the Front Range landscape slowly evolved under the influence of climate and weather, organic change, and geodynamic forces. Hardly perceptible day-to-day changes were accented by occasional exceptional events—a flood, a rockfall, a landslide, or a debris avalanche. But as a result of human activities, the Front Range Urban Corridor has seen a greater rate of change since the time of pioneer settlement in the last century, than at any time in the previous 30 million years.

Along the Front Range Urban Corridor, environmental stress intensifies when land development involves certain easily disturbed sediments such as loess, some eolian sand, organic loam, and expansive clay. It intensifies when excavations involve marginally stable hillslopes or penetrate the water table, when mineral extraction (gravel, clay, stone, coal) disturbs natural processes, or when urban development alters the hydrologic regimen. Some geologic/geomorphic processes in the Front Range Urban Corridor have resulted partly or wholly from human activity. Subsidence over coal mines, for example, has caused a collapse topography that has adversely altered the local landscape and could damage superincumbent structures. Some other processes are quite natural but in the urban environment have been heightened artificially—stream discharge and runoff are increased, for example, as are erosion and slope forming processes.

Human impacts on the environment tend to interact and multiply. For example, urbanization fosters highway construction and vice versa. Construction aggregate is excavated from a gravel pit that later is backfilled with urban refuse that reacts with seepage and generates leachate that seeps into the ground water. Noxious gases generated in the landfill escape to the atmosphere. Urbanization and, agricultural practices alter the soil chemistry and the natural runoff, which in turn affect water quality, water-table levels, erosion, and sedimentation. These in turn modify the habitat of aquatic organisms and the hydrologic amenity (Leopold, 1968). Adverse environmental impacts can sometimes be mitigated if geologic knowledge is applied to the solution of land-use problems. Environments change, but environmental quality can be maintained and enhanced if the cities, towns, highways, canals, reservoirs, airports, plowed fields, irrigated farms, mines, quarries, landfills, and myriad other enterprises of the Front Range are compatible with the natural dynamics of the biosphere. Four hundred years ago Sir Francis Bacon observed that "Nature to be commanded must be obeyed." But nature to be obeyed must also be understood (Robinson and Spieker, 1978).

This report summarizes the results of U.S. Geological Survey activities in the Front Range Urban Corridor area during the last decade. Though the field of activities is broad, the summary is generalized and nonspecific. It is intended more to call attention to basic data than to answer questions. The fairly numerous literature citations in the text serve as departure points for readers interested in more thorough pursuit of specific topics. Many more papers could have been cited. A truly vast literature (Chronic and Chronic, 1974) has accumulated through the years on the geology, hydrology, and related fields of the Front Range Urban Corridor.

GEOGRAPHIC FACTORS AND AREA

The Front Range Urban Corridor is neither a political nor a geographic entity, and its boundaries are indefinite. It means different things to different people. As limited by the 1:100,000-scale topographic maps, its boundaries are lines of cartographic convenience drawn to conform to standard lines of latitude and longitude while at the same time encompassing most of the area of probable urban expansion within the foreseeable future.

As thus drawn, the area is about 62 km (kilometers) wide west to east through most of its length and about 218 km long north to south. Near Colorado Springs it is about 33 km wide. It contains 79 $7\frac{1}{2}$-minute topographic quadrangles and has an area of nearly 12,000 km^2 (square kilometers). However, some planners and legislators in Colorado have come to regard the 'Front Range area" in a broader sense than that of this report. For administrative and statutory purposes, they have included cities such as Pueblo that are separated geographically from the more or less continuous urban corridor of cities and towns to the north. Pueblo has not yet shared the rapid growth of its neighbors to the north at the foot of the Front Range.

The Front Range Urban Corridor straddles the boundary of the Front Range, which is a major subdivision of the Southern Rocky Mountains, and the Colorado Piedmont section of the Great Plains (Fenneman, 1931, pl. 3). The Colorado Piedmont, insofar as the Front Range Urban Corridor is concerned, separates the Rocky Mountains from the High Plains and contains most of the State's population (fig. 1). Urbanization, however, is spreading into the mountains, particularly west of Denver but also west of other corridor communities. Although the entire area is drained by the South Platte and Arkansas Rivers and their tributaries, the mountains and plains communities have widely differing environments. Geology, hydrology, topography, soils, vegetation, climate and weather differ greatly from the plains to the mountains.

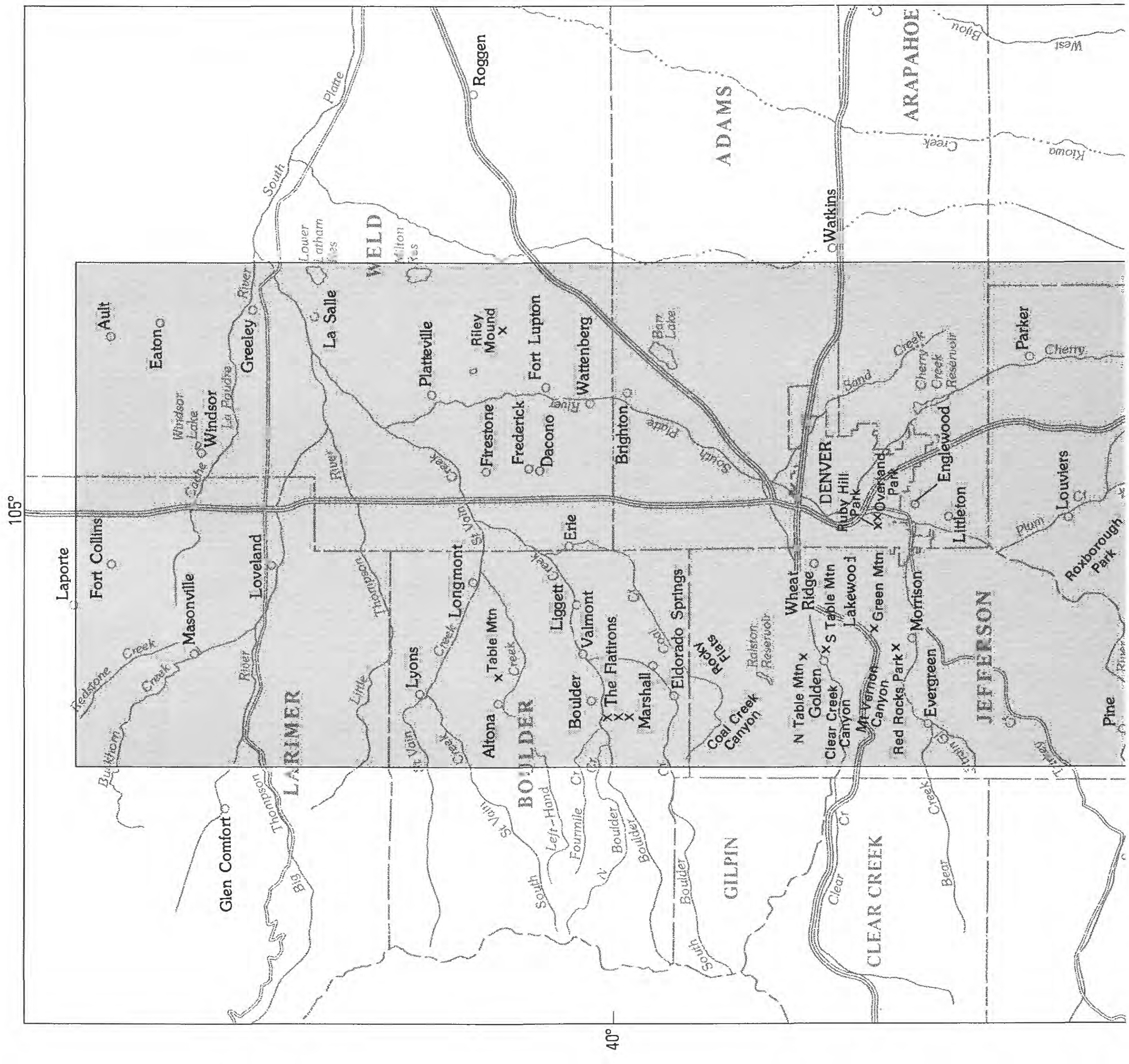
Because of its complex physiographic and geologic setting and its rapid growth rate, therefore, the Front Range Urban Corridor faces a host of land-use problems. Many of the problems have a geologic/geomorphic basis and the potential for large environmental impacts. They are related to foundation conditions and soils, slope stability, mineral extraction, urban hydrology, waste disposal, and perhaps, seismicity.

THE TOPOGRAPHIC MAP

The topographic map of the Front Range Urban Corridor consists of three sheets identified from north to south as the Boulder-Fort Collins-Greeley Area (sheet 1), the Greater Denver Area (sheet 2), and the Colorado Springs-Castle Rock Area (sheet 3). At the time the Front Range Urban Corridor project was started as a pilot study, much consideration was given to the kind and scale of topographic map on which to plot data drawn from all the diverse elements of the program. The basic topographic map would be an important product on its own merit—it would be widely used by people with varied needs and requirements. This judgement later proved to be correct, and the Greater Denver Area map soon had to be reprinted to meet the ongoing demand.

Several innovations were incorporated into the topographic map to serve the special needs of the project. One of the most important was scale. Other considerations—contour interval, map detail, line weight, preparation time, and cost estimates—all depended on scale. Subdivision planners might prefer the largest scale available, but regional planners require a smaller synoptic scale for showing regional relationships. The scale is determined by the need.

In view of the size of the Front Range Urban Corridor and the degree of detail desired, a scale of


105°
40°
LARIMER
WELD
ADAMS
ARAPAHOE
BOULDER
GILPIN
CLEAR CREEK
JEFFERSON
Laporte
Fort Collins
Ault
Eaton
Windsor
Windsor Lake
Greeley
Masonville
Loveland
La Salle
Lower Latham Res
Milton Res
Roggen
Platteville
Riley Mound
Fort Lupton
Wattenberg
Firestone
Frederick
Dacono
Brighton
Barr Lake
Watkins
Lyons
Longmont
Table Mtn
Altona
Erie
Liggett
Valmont
Boulder
The Flatirons
Marshall
Eldorado Springs
Rocky Flats
Ralston Reservoir
Coal Creek Canyon
N Table Mtn
Golden
Clear Creek Canyon
Wheat Ridge
S Table Mtn
Lakewood
Green Mtn
Morrison
Mt Vernon Canyon
Red Rocks Park
Evergreen
DENVER
Ruby Hill Park
Overland Park
Englewood
Littleton
Cherry Creek Reservoir
Parker
Louviers
Roxborough Park
Pine
Glen Comfort
South Platte
Cache la Poudre River
Big Thompson River
Little Thompson
St Vrain Creek
Left-Hand Cr
Fourmile Cr
Boulder Creek
Coal Cr
Clear Cr
Bear Creek
Plum Cr
Cherry Creek
Sand Creek
Bijou
Kiowa
Redstone Creek
Buckhorn

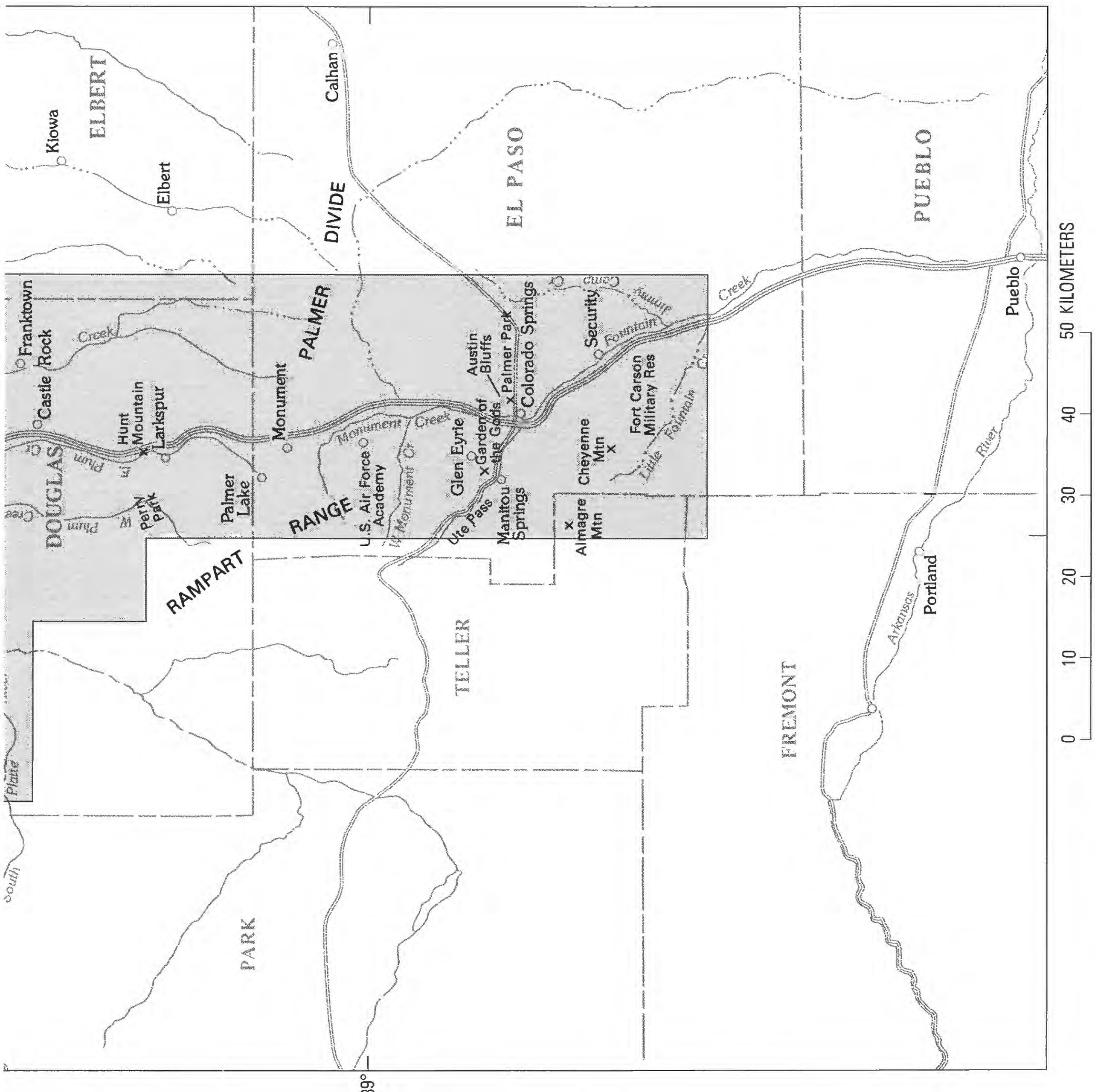


FIGURE 1.—Map showing place names in the Front Range Urban Corridor mentioned in text.

1:100,000 for the base maps was chosen after consideration of such scales as 1:95,040 (1.5 mi/in. (miles per inch)), 1:96,000 (8,000 ft/in. (feet per inch) and a fraction of the standard 1:24,000 scale), 1:125,000 (a multiple of the widely used quarter-million scale), and 1:126,720 (2 mi/in.). A scale of 1:100,000 had not previously been used by the U.S. Geological Survey, although it is widely used abroad and is now coming into general U.S. Geological Survey use. It preserves a synoptic map quality lacking at larger scales, without sacrificing the accuracy and detail missing from smaller scales. With the map spread out on a conference table, the user can view at a glance the geographic features of the entire Front Range Urban Corridor.

A scale of 1:100,000 was preferred to other nearly equal scales (that is, 1:96,000) because it is a step toward the metric system of measurements: 1 cm (centimeter) on the map equals 1 km (kilometer) on the ground. The metric scale, moreover, is particularly suited to computer treatment of map information. At the smaller scale of 1:125,000, which is not metric, the contour density in the mountains probably would have required an interval of no less than 200 ft (feet), which is manifestly too large for the plains. The finally adopted 100 ft interval with local supplemental 50-ft contours well portrays the regionwide topography.

For the best possible fit of map data to the base, a transverse Mercator projection was designed by cartographer Wesley S. Hupp, U.S. Geological Survey (retired). Because of the curvature of the earth, no flat map of a large area completely lacks distortion. The transverse Mercator projection, however, provides approximate equal-area coverage with minimal distortion for an area that is elongated north to south like the Front Range Urban Corridor. A meridian rather than the Equator is the circumference of tangency—here the 105th meridian, which bisects the area. In effect, the 105th meridian of the projection is in contact with the globe, and all other points on the ground are projected up to the imaginary plane of the projection in proportion to their distance from the circumference of tangency. Map distortion increases away from the 105th meridian but is negligible for an area the size and shape of the Front Range Urban Corridor.

Distinctive nonstandard treatments were used to show map features of special concern to the land-use planning community. Roads and streets are shown as single lines so that their map widths are approximately true to scale. Heavy-duty roads and paved streets are shown in red; light-duty roads, unimproved dirt roads, and trails are shown in black. This scheme eliminates the need for the rather arbitrary pink tint used to denote urban areas on conventional maps—the welter of red street lines creates its own pink tint. Other map features that have specific land-use significance are shown by distinctive tints also—for example, cemeteries, parks, recreation areas, airports, Federal installations, and woodlands. Standard colors are used for other map features: blue for water, brown for contours, and black for lettering, political boundaries, selected buildings, railroads, and marginal data.

LANDFORMS

The eastern slope of the Front Range section of the Southern Rocky Mountains forms the westernmost part of the urban corridor. It is paralleled along much of its length by a narrow zone of still lower sharp-crested foothill ridges, sometimes called the hogback belt (fig. 2). The part of the corridor east of this belt is in the western part of the Colorado Piedmont.

FRONT RANGE

Within the corridor, the eastern part of the Front Range rises as much as 1,450–1,525 m (meters) above the adjacent piedmont, reaching elevations of 2,700–3,000 m above sea level. Even higher mountains stand farther west. The sharp contrast between the mountains and the piedmont is a result of uplift and erosive resistance of the mountain belt. Narrow ridges and deep canyons characterize the mountain front, but many of the canyons widen upstream, the slopes flatten, and the ridge tops expand into rolling uplands. These subdued areas contain most of the small mountain towns and outlying mountain residential developments. Evergreen is such a development southwest of Denver on Bear Creek. Bear Creek flows through a narrow canyon along much of its length, but Evergreen and other small communities fill wide places.

HOGBACK BELT

The hogback belt along the mountain front rises from a few meters to as much as 300 m above the western border of the Colorado Piedmont. The hogbacks are the edges of steeply tilted, resistant sedimentary strata (fig. 3) that once covered the crystalline core of the Front Range. As the mountains rose, the sedimentary cover was eroded away, leaving the tilted strata at the mountain flanks. These strata extend far eastward at much gentler inclinations beneath the Colorado Piedmont and, still farther east, beneath the High Plains.

The basal beds of the hogback sequence can be seen lying against the crystalline rocks in many places along the mountain front, such as Red Rocks Park west of Denver. The hogbacks are separated from one another by narrow valleys cut into less resistant rocks

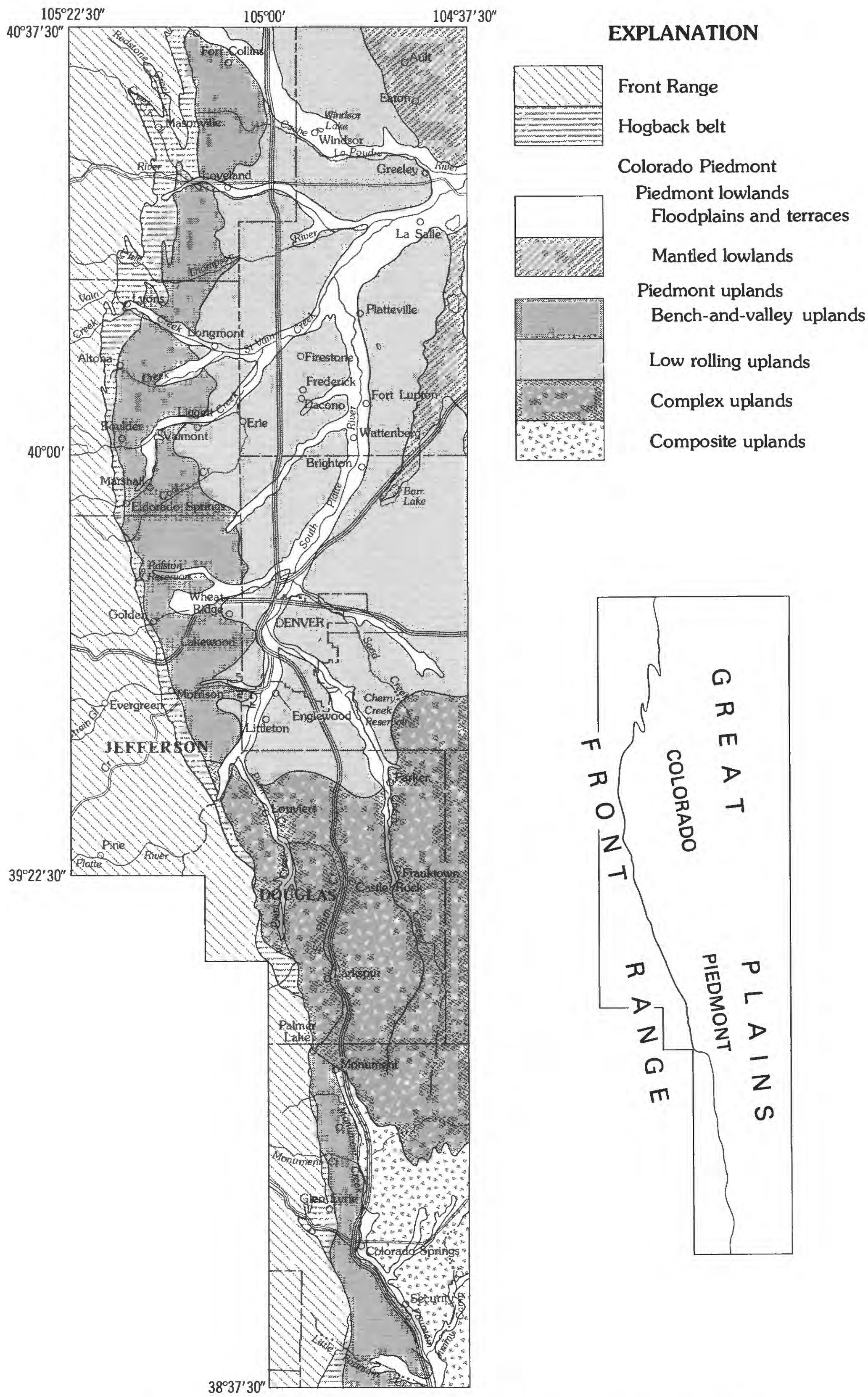


Figure 2.—Map showing landforms of the Front Range Urban Corridor.

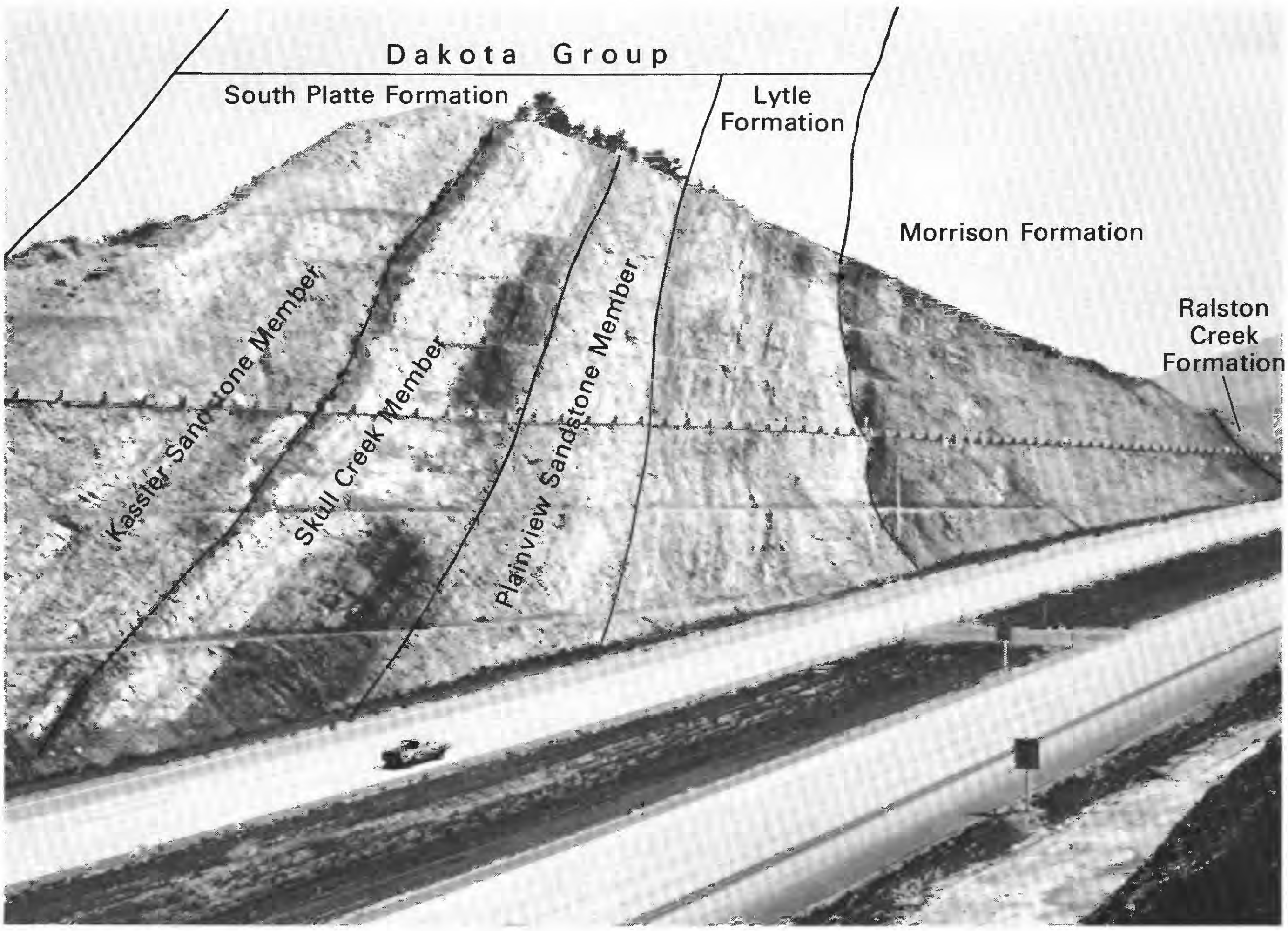


FIGURE 3.—Sequence of tilted strata at Interstate 70 roadcut through the hogback at Mount Vernon Canyon, Jefferson Co., July 1972, looking southward.

(fig. 4). Most of these valleys are floored with soil and rock debris from the adjacent ridges; landslides and rockfalls are common. Hill slopes commonly are steeper toward the mountains than toward the plains; they range from a few degrees to nearly vertical.

COLORADO PIEDMONT

The Colorado Piedmont section of the Great Plains extends along the Rocky Mountain front from a boundary near the Wyoming State line to an indefinite margin beyond Pueblo in southern Colorado. The piedmont is bounded on the east by the western border of the High Plains section of the Great Plains. The westernmost point of the High Plains is about 113 km southeast of Denver, and, thus, the High Plains are entirely east of the area, although many people mistakenly think that Denver and other corridor cities are on the High Plains. Only the western part of the piedmont, moreover, is within the Front Range Urban Corridor, but that part of the piedmont contains most of the corridor population.

In the geologic past, the High Plains extended west across what is now the piedmont to the mountain front, but the old surface has since been dissected by erosion so that none of it remains in the Front Range Urban Corridor. Some parts of the divide between the Arkansas and South Platte Rivers (Palmer divide and a few other areas), however, are close to the original High Plains surface. In the dissection process, erosion and down cutting have alternated with deposition. Loose sediment moved by wind also helped shape the piedmont. These processes have constructed a rolling surface that is subdued compared to the mountains but is more varied than the western High Plains.

The South Platte River drains northeastward across the northern three-quarters of the corridor. Fountain Creek drains southward in the southern quarter to join

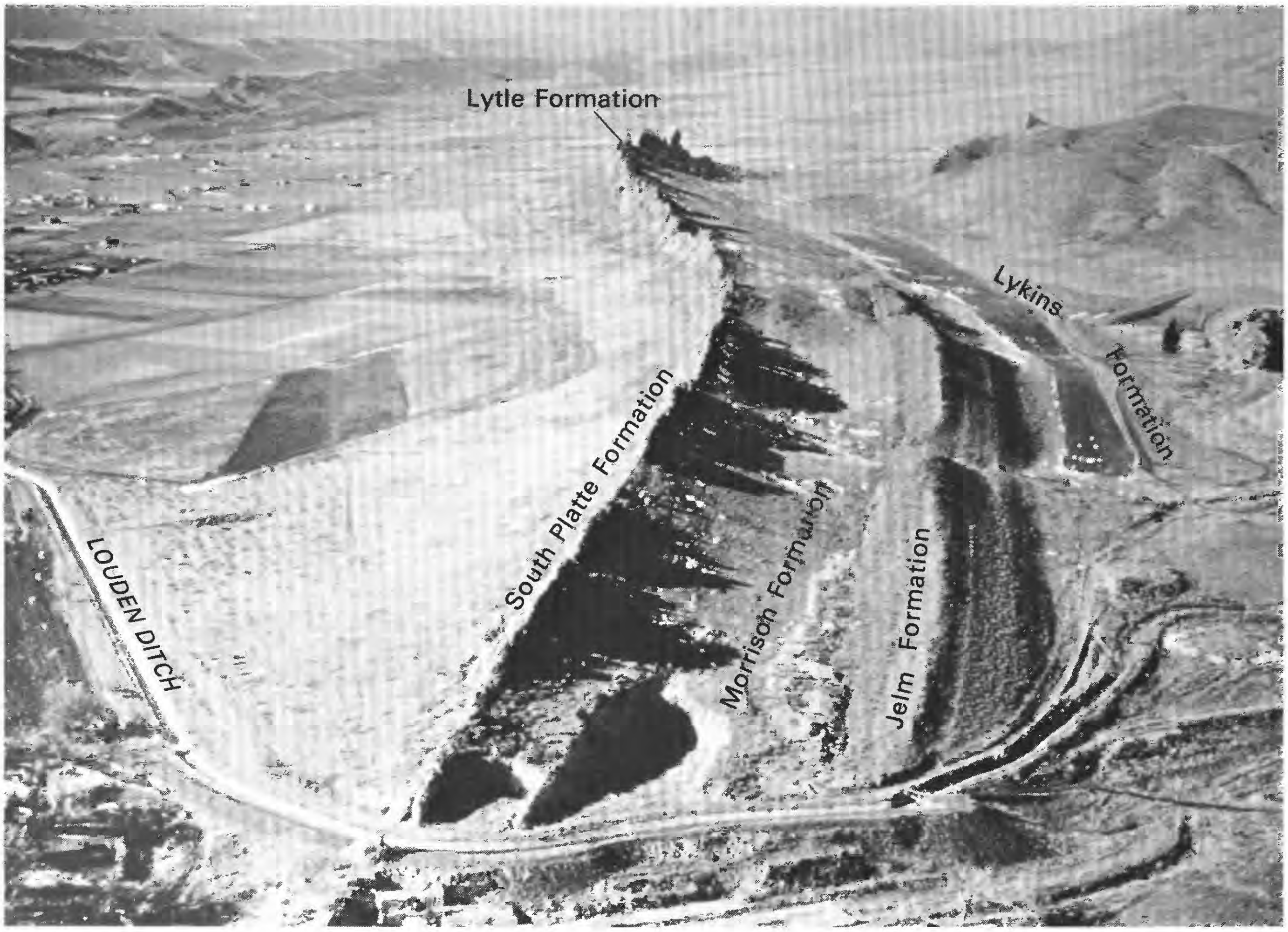


FIGURE 4.—Devils Backbone, near Loveland. Steeply dipping beds are on southwest flank of Big Thompson anticline. Resistant strata form hogbacks; easily eroded beds form strike valleys. Low-altitude aerial photograph, looking northwest, by Brent N. Petrie, planning consultant, April 1973.

the Arkansas River nearly 50 km south of the corridor boundary. Between the two drainage systems, the Palmer divide (the corridor segment of the South Platte-Arkansas divide) reaches above 2,300 m. Minimum elevations on the corridor are about 1,400 m on the South Platte east of Greeley and about 1,645 m on Fountain Creek south of Colorado Springs. The regional gradient from Palmer divide to exit points of the two principal streams is less than 2 percent (less than 10 m/km) to the south and less than 1 percent to the north. Many local landforms, however, are much steeper.

In this report, the landforms of the Colorado Piedmont are divided into lowlands and uplands. These broad groups are further divided into several categories. With few exceptions the boundaries between land forms are gradational.

PIEDMONT LOWLANDS

FLOOD PLAINS AND TERRACES

The piedmont lowlands include flood plains, terraces, and mantled lowlands. Flood plains are 1.5–3 km wide along the lower reaches of the South Platte River and its major tributaries in the northern half of the corridor. They decrease in width upstream and disappear from some of the smaller drainages. In the Fountain Creek drainage system in the southern part of the corridor flood plains are less than 1 km wide. The widths cited here are based on the approximate extent of 100-year flooding, as calculated by McCain and Hotchkiss (1975a, b, c). The broader flood plains are nearly flat bottom lands of very low relief. Slight surface irregularities are due to incised or abandoned channels and very low terraces, or to gravel pits and other human works.

One or more terraces border many of the flood plains at heights of about 3 m to 21 m (Colton, 1978; Trimble and Machette, 1979a, b). Terraces are more than 3 km wide along the lower reaches of the South Platte River, but elsewhere they are mostly less than 1 km. Well-preserved terraces are nearly flat; others are variously dissected.

MANTLED LOWLANDS

The mantled lowlands are in the northeast part of the Front Range Urban Corridor. The mantled lowland surface has very low irregularities related largely to wind deposition and erosion. Beebe Draw, between Greeley and Brighton, and the Eaton-Ault area north of Greeley are segments of former stream valleys covered by eolian (wind-blown) sand and silt. Beebe Draw contains a former channel of the South Platte River. Broad tracts of dune sand have been stabilized in most places by natural vegetation or cultivation, but in some places blowouts are occasionally activated by strong winds. Water entering the mantled lowlands moves in the subsurface or in manmade canals.

PIEDMONT UPLANDS

The term "uplands" is used here for all interstream areas on the Colorado Piedmont above the levels of flood plains and bordering terraces or above the mantled lowlands. The several upland categories are named according to their predominant landforms, but they contain other smaller areas, and the various landforms commonly grade into one another. With these qualifying factors in mind, we may divide the Colorado Piedmont into bench-and-valley uplands, low rolling uplands, complex uplands, and composite uplands.

BENCH-AND-VALLEY UPLANDS

The name "bench-and-valley uplands" is here applied to a zone about 3–16 km wide just east of the hogback belt. A bench, in this rather free usage, is a nearly flat tongue of land that slopes generally eastward at a low angle from the hogbacks or the mountain front. Some benches widen away from the mountains, as at Rocky Flats south of Boulder, and many are notched marginally by gullies. Bordering slopes are gentle or steep and smooth or gullied. Heights may be 60–120 m, but mostly are less. Where erosion has severed a bench from an adjacent hogback or mountain front, the free-standing, flat-topped landform is a mesa or, if the summit area is very small, a butte.

Nearly all benches, mesas, and buttes in the bench-and-valley uplands are capped with gravel that was deposited by streams flowing out of the mountains in the geologic past, when the benches were the valley floors.

Valleys between benches have been partly or completely stripped of a once more extensive gravel capping. Present-day streams are small, and they only intermittently have enough water to cause erosion. Where tilted strata crop out, a complex of low ridges, flats, and hollows contrasts with the smoother surfaces of the benches.

Bench-and-valley topography is well formed in the U.S. Air Force Academy area north of Colorado Springs, in the Rocky Flats area south of Boulder, and in and north of Boulder. Table Mountain north of Boulder is a good example of a gravel-capped mesa in the bench-and-valley zone. (North and South Table Mountains at Golden are mesas capped by lavas rather than gravel.)

LOW ROLLING UPLANDS

Low rolling uplands extend from the northern boundary of the Front Range Urban Corridor southward 24–29 km beyond the center of Denver and from the bench-and-valley uplands on the west to the east edge of the corridor. With few exceptions, the relief is lower than on other parts of the piedmont. In interstream areas, the proportion of bordering slope to upper surface is generally small except at the transition to the bench-and-valley uplands. This transition is especially noticeable north of Denver along the west side of the South Platte River to about the latitude of Boulder.

The subdued topography of much of the low rolling uplands is caused by a cover of eolian silt and sand, which is extensively farmed. In a few places, however, the soil cover is too thin to mask the irregularities of underlying bedrock which, locally, is exposed. Isolated remnants of gravel top a few of the higher hills.

The western and southern margins of the low rolling uplands generally correspond with the limits of widespread eolian silt and sand. These margins are about 1,555–1,585 m above sea level near Fort Collins and 1,770–1,860 m south of Denver. The lowest areas are slightly above 1,400 m, in the South Platte valley near Greeley. Local relief rarely exceeds 75 m and in most places is less than 30 m.

COMPLEX UPLANDS

The term "complex" refers to a diversity of landforms controlled by variations in bedrock. Generally the surface is rocky or is covered by residuum weathered from the bedrock itself. The bedrock surface is mantled in only a few places by eolian sediments and ancient river gravels. The complex uplands extend from the southern boundary of the low rolling uplands south across the Palmer divide, where elevations are above 2,300 m, and down the shorter slope south of the divide to elevations between 2,135 and 2,170 m. The southern boundary is the approximate upper limit of eolian mantle in the adjoining composite uplands division of the piedmont. Locally on the north slope of the Palmer divide the complex-uplands surface reaches west to the mountain front, breaking the continuity of the hogback ridges.

The complex uplands are divisible into two major groups of landforms having many variants. The more conspicuous forms are mesas, buttes, and transitional features. Some larger, free-standing buttes and mesas rise 150 m or more above their surroundings, but many are much lower. Typically they are capped by cliff-forming rimrocks of sandstone, conglomerate, or volcanic rock overlying weaker slope-forming sedimentary rock. Upper surfaces are slightly undulatory, but where erosion is far advanced, the summits are reduced to narrow ridges or points. Included in this more-conspicuous first group are mesalike uplands that merge with the uncapped less-conspicuous interdrainage ridges of the second group of landforms. The largest of the incompletely developed mesas extends from Castle Rock east and southeast beyond the border of the corridor. Cherry Creek and some of its tributaries have notched or cut completely through the northern bluffs of this mesa to depths of as much as 90 m; East Plum Creek and its tributaries have shaped the western margin.

The second group of landforms in the complex upland consists of interdrainage ridges without resistant cappings underlain by easily eroded sandstone, mudstone, and claystone. The resultant topography contrasts with the broad-topped mesas, and it also differs from the interstream areas of the low rolling uplands to the north. The landscape is much more closely dissected than most of the low rolling uplands, where minor drainage courses are so shallow that they are not shown by 10-ft (3-m) contours on a topographic map. Also, in the ridge-dominated areas of the complex uplands, slope width generally exceeds summit width, except high on the north side of the Palmer divide, where broad ridge summits dominate an open rolling landscape. Even there, however, many of the ridges have definable crest lines.

The upper south slope of the Palmer divide is slightly steeper in most places than the upper north slope, and it supports a dense coniferous forest; much of the north slope is open forest or grassland. The forest on the south slope tends to obscure details of dissection and ground roughness, although the uppermost south slope is about as dissected as the uppermost north slope. In and below the eastern part of the forest fringe on the south slope, however, shallow dissection has produced an intricate pattern of gullies separated by many knobby ridges.

COMPOSITE UPLANDS

The area east of Monument and Fountain Creeks, from the southern border of the complex uplands to the southern border of the Front Range Urban Corridor, contains landforms characteristic of all of the other divisions of the piedmont. Because no one landform predominates, this division is designated as composite uplands. Remnants of ancient river gravels may once have been continuous with gravels on the bench-and-valley uplands to the west. Parts of the area resemble the low rolling uplands in the northern part of the corridor; eolian sand and silt cover much of both places. Elsewhere, as in the complex uplands, differences in bedrock dictate the landform; examples are the sandstone bluffs north and northeast of Colorado Springs (Palmer Park, Austin Bluffs, and other unnamed bluffs) and the canyonlike valley of Jimmy Camp Creek. Flood plains and terraces also are present.

CLIMATE

Astride the boundary between the Great Plains and the Southern Rocky Mountains, the Front Range Urban Corridor has a varied climate. Many local differences result from the infinitely varied topography and aspect (exposure) and from variations in altitude in the different parts of the area. Natural variations, moreover, are modified by the climatic effects of urbanization, which not only alter local temperature, circulation, and cloudiness, but also degrade the air quality around the larger communities.

The climate of the Colorado Piedmont is semiarid temperate continental, sometimes referred to as a "middle latitude steppe" (Trewartha, 1961, map facing p. 8). In parts of the adjacent foothills the climate is subhumid. Mean annual precipitation within the corridor ranges from about 280 mm near Greeley on the piedmont to more than 650 mm in the mountains west of Boulder. Monthly mean temperatures on the piedmont range generally from about 21° C in July to about -2° C in January. The maximum for any one month may vary from about 38° C in summer to about 16° C in winter. Extreme low temperatures range from around -30° to -40° C. Temperatures are nearly always cooler in the mountainous parts of the corridor than on the plains, but winter temperatures are sometimes lower on the plains when shallow, blanketlike inversions spread across the plains but fail to reach into the mountains.

A capsule summary of the climate of the Front Range Urban Corridor (Hansen and others, 1978, p. 58) includes the following:

- Highly variable weather elements (temperature, humidity, cloudiness, precipitation, and wind) along the Front Range and the Colorado Piedmont; areas of higher altitude in general have lower mean temperatures, greater cloud cover, greater precipitation, and greater variability in other weather elements.
- Strong seasonal variations of most weather elements.
- General semiaridity at the lower altitudes, with average rainfall of 300–350 mm per year on the Colorado Piedmont and 400–500 mm or more in the mountains.
- About 70 percent of the precipitation in the warm season between April and September.
- Completely clear weather over most of the area on about half the days.
- Cloudy weather less than a third of the time over two-thirds of the area.
- A persistent, well-defined heat island over the Greater Denver area caused by broad expanses of heat-absorbent and heat-radiant material, such as streets and buildings, and by the release of artificially generated heat.
- A persistent climatic ridge extending eastward across the Colorado Piedmont in the vicinity of the Palmer divide, caused by the orographic effect of the divide on local air masses.
- A north-south belt of occasionally very strong foehn or chinook winds, especially in winter, concentrated in the foothills and the immediately adjacent piedmont.
- Frequent temperature inversions along the valleys of the South Platte River and Fountain Creek, especially in winter.

GEOLOGY

The geology of the Front Range Urban Corridor is presented here in three forms. The first is a tabulation of formations, designed to show quickly the relations of the rock units in the southern, central, and northern parts of the corridor (table 1). The second is a listing of the rock units, from younger to older, with a brief description and notes on thickness and distribution for each unit. The third section is a narrative account of the geologic history of the corridor and, in part, the surrounding areas. These presentations are based on the geologic maps of the Front Range Urban Corridor (Colton, 1978; Trimble and Machette, 1979a, 1979b) and on the extensive geologic literature that preceded these maps. Only a few of the many papers available have been cited—mostly publications that summarize or supplement the main body of knowledge regarding the Front Range Urban Corridor. These papers provide additional citations from the literature.

DESCRIPTIVE OUTLINE OF ROCK UNITS[1]

Quaternary

Lower level alluvial deposits (Holocene and Pleistocene)

Variably sorted gravel, sand, silt, and clay; cobbly to bouldery along major streams, becoming sandier eastward; poorly to well sorted, well stratified; soil profiles poorly to well developed. Form valley-fill terraces. Major units, from younger to older: post-Piney Creek alluvium and Piney Creek Alluvium, dark gray to brown, humic (about 2–11 m thick and less than 12 m above present stream levels); Broadway Alluvium, yellowish brown (less than 2–38 m thick (locally including Louviers) and 0–13 m above present stream level); Louviers Alluvium, yellowish to reddish brown (9–12 m thick and 2–21 m above present stream level).

Upper-level alluvial deposits (Pleistocene)

Cobbly, bouldery gravel near mountain front and along major streams, finer grained (sand, silt, and clay) on tributaries and eastward; generally poorly sorted, moderately to well compacted, stratified; commonly contains calcium carbonate that coats and cements gravels; soil profiles well developed, some truncated by erosion. Deposited as thin pediment gravels and thicker alluvial-fan or terrace gravels on stream-cut surfaces of bedrock (pediments). Major units, from younger to older: Slocum Alluvium (6–7 m thick and 24–40 m above present stream levels); Verdos Alluvium (3–6 m and 60–76 m); Rocky Flats Alluvium (3–15 m and 73–107 m); Nussbaum alluvium (2–24 m and 167–213 m); pre-Rocky Flats alluvium (1–2 m and 103–115 m).

Eolian sand, silt, and clay (Holocene to upper Pleistocene)

Loess (silt and subordinate fine sandy silt and clay) and sheets or dunes of fine to coarse sand, less than 1 m to 15 m thick, blanket much of the corridor east of the foothills. Source of commercial sand near Colorado Springs.

Other surficial deposits (Holocene and Pleistocene)

Landslide deposits, active and inactive: rock and soil debris, bouldery to sandy with a variable content of silt and clay; usually formed by moderately slow to very rapid downslope mass movement induced by gravity and, commonly, water saturation. Colluvium: unconsolidated rock and soil debris slowly moved downward and deposited on slopes by gravity and slopewash processes. Includes talus at base of steep cliffs.

Tertiary

High-level gravel deposits (Pliocene to Oligocene)

Rounded to subangular pebbles, cobbles, and boulders generally 1–2 m in maximum dimension but as much as 6 m in diameter, in a sandy matrix. Stones are chiefly granite and other Precambrian rocks, but include Tertiary volcanic rocks in the southern part of the corridor; 150–300 m above present main streams.

[1] Compiled from Braddock and others (1970), Colton (1978), Crosby (1976), Grose (1960), Larson and Hoblitt (1973), Maberry and Lindvall (1972), Maughan and Wilson (1960), Pipiringos and O'Sullivan (1976), Scott (1972d), Scott and Wobus (1973), Trimble and Machette (1979a, b), Tweto (1975, 1976), Tweto and Sims (1963), Van Horn (1976), Walker and Harms (1972), and Weimer and Land (1972a, b).

Tertiary—Continued

Castle Rock Conglomerate (lower Oligocene)

Bouldery cobbly gravel in a sandy matrix; includes mudstone, claystone, siltstone, and sandstone in eastern part of corridor. Stones are Precambrian rocks and subordinate chert and Tertiary volcanics; gravel matrix well cemented by silica, locally less well cemented near base. Generally less than 15 m thick.

Wall Mountain Tuff (lower Oligocene)

Light-gray, fine-grained rhyolitic volcanic rock (74 percent silica) composed mostly of devitrified glass shards. Formed as an ash-flow sheet; probably less than 15 m thick.

Quartz monzonite (Eocene)

Small irregular intrusive bodies and stocks of fine- to medium-grained quartz monzonite in the northwest part of the corridor, associated with the Colorado mineral belt (Tweto and Sims, 1963).

Green Mountain Conglomerate (Paleocene)

Conglomerate, in part andesitic, and subordinate sandstone, siltstone, and claystone; contains Paleocene pollen and fossil plants. Thickness about 198 m. Preserved only on Green Mountain, south of Golden.

Lava flows and small intrusive masses (Paleocene)

Dark-gray porphyritic lava flows, three on North Table Mountain and two on South Table Mountain at Golden (Van Horn, 1976, p. 47), are tentatively correlated with an intrusive dike of similar composition near Ralston Reservoir that may have been the feeder for the flows. Other intrusive rocks, mostly sills, between Golden and Lyons are of about the same age. Maximum thicknesses of individual flows range from about 18.3 m to about 52.4 m. The Ralston dike and the Valmont dike east of Boulder were called alkalic basalt by Larson and Hoblitt (1973); other geologists have used the names monzonite or shoshonite for the intrusives and mafic latite or shoshonite for the flows (Van Horn, 1976; Scott, 1972d) Larson and Hoblitt designated other intrusives, northward toward Lyons, as rhyodacite.

Tertiary and Mesozoic

Dawson Arkose (Paleocene to Upper Cretaceous)

Dominantly lenticular, locally crossbedded, white to yellowish-gray or brown arkosic conglomerate or coarse sandstone, siltstone, and olive-brown to variegated claystone. Contains lignite in Adams and Arapahoe Counties and the Kassler area and two zones characterized by andesitic pebbles and finer detritus near Colorado Springs. Maximum thickness about 750 m. In part may be laterally equivalent to Green Mountain Conglomerate, Denver Formation, and Arapahoe Formation in the Denver metropolitan area; data published by Soister (1978, p. 227, fig. 2) indicate that the lower member of the Dawson Arkose is no older than late Paleocene, the main body of the Dawson is of Eocene age, and the formation overlies the Denver Formation where both units are present.

Denver Formation (Paleocene to Upper Cretaceous)

Brown to olive fluvial claystone, siltstone, sandstone, and conglomerate; interbedded mudflows contain pebble- to boulder-size blocks of rock in a clayey to sandy matrix. The Denver is derived predominantly from andesitic volcanic rock, locally as much as 95 percent. The tuffaceous sandstone and finer grained rocks contain montmorillonite that swells when wet and may damage houses, roads, and other construction. Thickness as much as 280 m. Formation largely restricted to the Denver metropolitan area. Probably equivalent to and intertongues southward with the middle and upper parts of the Dawson Arkose; at Golden is interbedded with Paleocene lava flows in North and South Table Mountains. Upper part contains mammal bones, lower part contains dinosaur remains and fossil leaves and wood.

Mesozoic

Arapahoe Formation (Upper Cretaceous)

Lenticular deposits of gray to brown fine- to coarse-grained sandstone, siltstone, claystone, and thin pebble beds in the upper part; coarser sandstone and pebble-to-cobble conglomerate in the lower part. Sedimentary rock fragments exceed igneous and metamorphic rock fragments in the lower conglomeratic beds; proportions are reversed in the upper beds. Formation grades into lower part of Dawson Arkose. Contains ironstone concretions and dinosaur bones. Thickness about 120–150 m.

Laramie Formation (Upper Cretaceous)

Upper part mostly claystone and siltstone or shale interbedded with subordinate sandstone and thin local lignite beds; beds commonly pinch out within a few kilometers. Lower part contains more sandstone than siltstone or claystone and includes several subbituminous coal beds as much as 4.3 m thick, but usually thinner, above the basal sandstone. Contains fossil plant remains. Thickness about 170–300 m. Some geologists believe the basal sandstone is part of the Fox Hills Sandstone.

Fox Hills Sandstone (Upper Cretaceous)

Interbedded gray to brown sandstone and shale; massive or crossbedded sandstone predominates in upper and lower parts of formation in various localities. Limestone concretions locally in shale; calcareous iron-stained sandstone concretions in the generally poorly to moderately cemented sandstones. A transition zone of marine to nonmarine beds contains marine invertebrate fossils and finely broken plant fragments. Thickness about 18–152 m.

Pierre Shale (Upper Cretaceous)

Olive-gray to brown marine shale, siltstone, and silty sandstone; bentonitic shale in the lower part of the formation, limestone masses that weather into conical mounds (teepee buttes) in the middle part; calcareous concretions and calcareous shale in some zones. In the northern part of the corridor, upper, middle, and lower shale units are separated by an upper sandstone unit (Richard, Larimer, and Rocky Ridge Sandstone Members) and a lower ridge-forming Hygiene Sandstone Member; the Terry Sandstone Member is within the middle shale unit. A transition zone at the top of the formation grades upward from shale to increasingly more sandstone. Thickness of the formation is more than 2,600 m in the north but thins to about 1,143–1,585 m in the south.

Niobrara Formation (Upper Cretaceous)

Smoky Hill Shale Member: yellowish-gray to yellowish-brown, thin-bedded, soft, calcareous shale and interbedded thin, impure, commonly chalky limestone. Locally contains thin bentonite and selenite layers. Thickness 70–162 m. Contains marine fossils. Fort Hayes Limestone Member: yellowish-gray, thin- to thick-bedded, dense, hard limestone. Contains a few thin, calcareous shale partings and bentonite. Thickness 6–12 m. Contains marine fossils.

Benton Shale (Upper and Lower Cretaceous): equivalents of Benton are Carlile Shale and Greenhorn Limestone (Upper Cretaceous) and Graneros Shale (Upper and Lower Cretaceous). Carlile Shale: olive-gray to dark-gray, noncalcareous, silty, claystone and partly sandy siltstone in the northern part of the corridor; gray-brown, hard calcarenite, gray, silty sandstone, and yellow-gray, soft, calcareous shale in the southern part. Greenhorn Limestone: dark-gray limestone and olive-gray, calcareous, silty claystone and siltstone in the north; black to light-gray, noncalcareous clay shale, a few thin limestone interbeds, and several bentonite beds in the Golden area; and dense gray limestone, calcareous shale, and shaly calcarenite containing a basal marker bed of bento-

Mesozoic—Continued

Benton Shale—Continued

nite in the south. Graneros Shale: dark-gray to black, noncalcareous siltstone, claystone, or clay shale. Total thickness is about 90 m (south) to 200 m. Sparse marine fossils.

Dakota Group (Lower Cretaceous)

South Platte Formation: Two or three sandstone members (names vary with area), light-gray to brown, thin- to thick-bedded, commonly crossbedded and locally ripple-marked, fine- to coarse-grained, soft to very hard; dark-gray to black clay shale or claystone and gray to white refractory clay lenses or beds between the sandstone members. Thickness commonly about 8–11 m. Nonmarine and marine fossils indicate that this formation was deposited in shifting deltaic and shallow-marine environments. Resistant sandstone forms the most prominent hogback ridge along the mountain front and in places also forms a secondary ridge. Lytle Formation: Light-colored, lenticular, crossbedded, partly conglomeratic sandstone interbedded with sandy or silty, greenish to varicolored claystone. Thickness commonly 15–30 m.

Morrison Formation (Upper Jurassic)

Varicolored gray, maroon, and green siltstone and claystone and thin beds of sandstone, limestone, marl, and conglomerate. In the central part of the corridor, the formation contains a light-gray thin bedded, crossbedded, or massive commonly lenticular basal sandstone 3–12 m thick. Total thickness about 68–122 m. Contains fossil algae, freshwater mollusks, dinosaur bones, and plant remains.

Ralston Creek Formation (Upper Jurassic)

Greenish-gray to varicolored siltstone, claystone, and sandstone; associated with impure freshwater, partly algal limestone in some areas and with disseminated or bedded gypsum in others. Commonly contains grains, nodules, streaks, or thin beds of red to gray jasper. Reported maximum thickness is about 6 m near Colorado Springs and Boulder, and about 31–84 m in areas between. Some geologists correlate the upper part of the Ralston Creek with the lower part of the Morrison Formation, and the lower part of the Ralston Creek with the Canyon Springs Member of the Sundance Formation north of Boulder.

Sundance Formation: Windy Hill Member (Upper Jurassic); Pine Butte and Canyon Springs Members (Middle Jurassic)

Windy Hill Member: Gray to brownish gray thin-bedded ripplemarked sandstone with shale partings. About 3–5 m thick. Tongues out north of Loveland (Pipiringos and O'Sullivan, 1976). Pine Butte Member: massive, light-yellowish-gray sandstone, 1–3 m thick. Recognized in the corridor only north of Fourmile Canyon Creek north of Boulder (Pipiringos and O'Sullivan, 1976). Canyon Springs Member: calcareous, crossbedded, fine-grained sandstone, pink to grayish white, about 3–10 m thick. Grades southward into lower part of Ralston Creek Formation in vicinity of Boulder.

Jelm Formation (Upper Triassic)

Pinkish-gray crossbedded, fine- to medium-grained, calcareous sandstone, 6–43 m thick. Present in corridor only north of Fourmile Canyon Creek north of Boulder.

Mesozoic and Paleozoic

Lykins Formation (Triassic to Permian)

Maroon, grayish-red, and reddish-brown thin- to thick-bedded silty shale and calcareous siltstone and claystone; some green siltstone layers; silty sandstone; and gray to pale-red and reddish-brown wavy laminated limestone. Members, from youngest to oldest, include Strain Shale Member of LeRoy (1946), Forelle or Glennon Limestone Member, and Bergen Shale, Falcon Limestone, and Harriman Shale Members of LeRoy (1946). Total thickness about 55 m (south) to 205 m (north).

Paleozoic

Lyons Sandstone (Permian)

Yellowish to pinkish-gray to red, crossbedded, quartzose sandstone; includes arkosic conglomerate and conglomeratic sandstone in parts of the central and southern corridor, and subordinate tabular sandstone and thin beds of mudstone farther north. Thickness is 213–244 m near Colorado Springs, 108 m near Boulder, and 6 m near Fort Collins where all but the uppermost part of the formation has graded northward into the Satanka Formation.

Satanka and Ingleside Formations (Permian)

Red siltstone and fine-grained, thin-bedded, ripple-laminated sandstone (Satanka) and red, fine- to medium-grained, crossbedded, calcareous sandstone (Ingleside). Thickness about 103 m. Present only in northern quarter of corridor.

Fountain Formation (Lower Permian and Pennsylvanian)

Maroon, reddish-brown, and gray crossbedded, arkosic sandstone, conglomeratic sandstone, and conglomerate interstratified with horizontally laminated to thick-bedded, dark-red or green micaceous siltstone or mudstone and minor gray to pinkish-gray quartzose sandstone. In the Colorado Springs area, a basal unit, the Glen Eyrie Shale Member, consists of about 30 m of gray sandstone, sandy shale, and black shale. Thickness of the formation is about 1,340 m in the southern part of the corridor, 210 m in the northern part. The upper part of the nonmarine Fountain Formation grades into the partly marine Ingleside Formation in the northernmost part of the corridor.

Leadville Limestone (Mississippian) and Williams Canyon Limestone (Devonian)

Dark-gray, hard, dense limestones, about 40 m thick. Present in the southern part of the corridor only.

Harding Sandstone (Middle Ordovician)

Gray to white, fine-grained, thin-bedded sandstone and reddish-brown, sandy shale; about 20 m thick. Present in the southern part of the corridor only.

Manitou Limestone (Lower Ordovician)

Reddish-gray to buff, thin- to thick-bedded or massive, dense or granular limestone; in part nearly pure limestone, in part dolomitic, locally sandy. Thickness about 57 m. Present in southern part of corridor only.

Peerless Dolomite (Upper Cambrian)

Dark-red, finely to coarsely crystalline, thin-bedded dolomite. Thickness about 12 m. Present in southern part of corridor only.

Sawatch Sandstone (Upper Cambrian)

White, pink, reddish-brown, and locally green-mottled, fine- to coarse-grained, hard sandstone, thick to thin bedded, partly crossbedded; contains some conglomerate. Thickness about 7.6 m. Present in southern part of corridor only.

Precambrian

Pikes Peak Granite (Proterozoic Y)

White to orange-pink, medium- to coarsely crystalline biotite or biotite-hornblende granite, granodiorite, and quartz monzonite. Weathers to disaggregated mass of consitituent minerals. Age about 1,040 m.y. Several variants identified in southern third of corridor.

Silver Plume Quartz Monzonite (Proterozoic Y)

Yellowish-orange to reddish-gray, equigranular, fine- to medium-grained biotite-muscovite quartz monzonite; locally medium to coarse grained, porphyritic. Age about 1,440 m.y.

Precambrian–Continued

Boulder Creek Granodiorite (Proterozoic X)

Light- to dark-gray, medium- to coarse-grained gneissic granodiorite; locally porphyritic and may include some quartz monzonite. Some quartz monzonite in the southern part of the corridor is slightly younger than the Boulder Creek. Tonalite (quartz diorite) in the northern part may be slightly older than the Boulder Creek. Age about 1,710 m.y.

Pegmatite (Proterozoic Y or X)

Very coarse grained lenses, dikes, and irregular intrusive bodies composed mainly of quartz, feldspar, and mica. May be genetically related to one, two, or all three of the major Precambrian intrusive rock units of the corridor.

Metamorphic rocks (Proterozoic X)

Several varieties of gneiss, schist, quartzite, amphibolite, hornblendite, and other rocks metamorphosed from preexisting sedimentary or igneous rocks.

GEOLOGIC HISTORY

INTRODUCTION

The geologic history of the Front Range Urban Corridor, which spans at least 1 3/4 b.y. (billion years), has been divided for this report into eight time intervals of unequal length. By far the longest interval is the Precambrian. It also is the oldest, the most complex in terms of geologic processes, and the most obscured by subsequent events. A brief discussion of the Precambrian is followed by a longer description of later times during which relatively stable episodes alternated with intense geologic disturbances in and near the Front Range Urban Corridor.

In preview, a broad, low plain lay submerged at the end of Precambrian time beneath a shallow seaway in the region of the Southern Rocky Mountains. Three ensuing intervals of relative crustal stability—the second and the third successively shorter than the first—were followed by orogeny (mountain building) and other crustal disturbances. The first orogeny began in the Pennsylvanian Period, the second late in the Cretaceous Period, and the third in the Miocene Epoch of the Tertiary Period. Even under the comparatively stable conditions of early and middle Paleozoic time, gentle sagging and crustal upwarping reshaped the shallow seaway during its several advances and withdrawals across the region. Similar changes in areas of erosion, flooding, and deposition followed in Mesozoic time after the late Paleozoic uplift of the ancestral Rocky Mountains and before the late Mesozoic rise of the Laramide mountains (fig. 5). With the onset of the Laramide orogeny, the sea withdrew for the last time. The third and shortest interval of crustal stability was in the Eocene and Oligocene Epochs, when late Eocene erosion and deposition were followed by extensive Oligocene outpourings of lava and volcanic ash. In and after Miocene time, faulting, uplift, erosion, and deposition led to the elevation of the present Front Range and the shaping of the mountains and the piedmont.

PRECAMBRIAN TIME

At the end of Precambrian time (about 570 m.y. ago), the Southern Rocky Mountain region was a low plain eroded to the crystalline roots of earlier formed mountains. These roots were a complex of gneiss, schist, and quartzite derived from pre-existing sedimentary, volcanic, and plutonic igneous rocks. They had been metamorphosed under conditions of deep burial, intense pressure, and high temperature (fig. 6), and they had been invaded by granitic magmas during three major periods of intrusion: Boulder Creek Granodiorite, Silver Plume Quartz Monzonite, and Pikes Peak Granite intrusions. Numerous compositional variants and countless pegmatite dikes accompanied the major intrusions.

EARLY AND MIDDLE PALEOZOIC TIME

In early and middle Paleozoic time, the Southern Rocky Mountain region was a moderately stable area of low relief within the interior of the continent. Gentle warps and sags allowed shallow epicontinental seas to enter and leave the region, most often from the west or northwest, but sometimes also from the east and southeast. Erosion of high land farther west, of low eastern border lands, and of ephemeral islands and peninsulas within the inundated region supplied sand and mud to the seas and tidal flats; the marine waters themselves yielded calcareous and dolomitic sediments. The resulting sandstone, shale, and carbonate rocks were generally less than 300–450 m thick (Berg, 1960; Rothrock, 1960). Numerous low-angle discordances or irregular surfaces between sequences of beds record times and places of slight unwarping, nondeposition, and erosion. Silurian through Middle Devonian rocks were long thought to be entirely absent from this region, but blocks of fossil-bearing Silurian limestone found in the rocky fillings of ancient volcanic vents near the Wyoming-Colorado border indicate that Silurian marine rocks once covered at least part of the Southern Rocky Mountain region. All other traces of their presence seem to have been removed (Chronic and others, 1969).

Lower to middle Paleozoic rocks within the Front Range Urban Corridor have a maximum probable thickness of less than 150 m. They are now exposed only along the mountain front of the Rampart Range and in the embayment of the mountain front at Manitou Springs west of Colorado Springs. To the east they are deeply buried in the subsurface. If they were once more extensive in the corridor area, as seems likely, they were removed by erosion before deposition of the later Paleozoic sediments.

TABLE 1.—*Rock units in the Front Range Urban Corridor, Colorado*

<table>
<tr><th>ERATHEM</th><th>SYSTEM</th><th>SERIES</th><th>COLORADO SPRINGS–CASTLE ROCK AREA</th><th colspan="2">GREATER DENVER AREA</th><th colspan="2">BOULDER–FORT COLLINS–GREELEY AREA</th></tr>
<tr><td rowspan="7">CENOZOIC</td><td>QUATERNARY</td><td>Holocene and Pleistocene</td><td colspan="5">Lower level alluviums (terrace deposits); upper level alluviums (pediment gravels and associated deposits); windblown sand, silt, clay; other surficial deposits (landslide, colluvium, talus)</td></tr>
<tr><td rowspan="6">TERTIARY</td><td>Pliocene and Oligocene</td><td colspan="5">High-level gravel deposits</td></tr>
<tr><td rowspan="2">Lower Oligocene</td><td>Castle Rock Conglomerate</td><td colspan="2">Castle Rock Conglomerate</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>Wall Mountain Tuff</td><td colspan="2">Wall Mountain Tuff</td></tr>
<tr><td>Eocene</td><td></td><td colspan="2"></td><td colspan="2">Quartz monzonite</td></tr>
<tr><td rowspan="2">Paleocene</td><td rowspan="4">Dawson Arkose[1]</td><td colspan="2">Green Mountain Conglomerate</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Denver Formation</td><td>Table Mtn. Shoshonite – Lava flows, intrusives</td><td colspan="2">Small intrusive bodies</td></tr>
<tr><td rowspan="10">MESOZOIC</td><td rowspan="10">CRETACEOUS</td><td rowspan="9">Upper</td><td></td><td colspan="2"></td></tr>
<tr><td colspan="2">Arapahoe Formation</td><td colspan="2"></td></tr>
<tr><td>Laramie Formation</td><td colspan="2">Laramie Formation</td><td colspan="2">Laramie Formation</td></tr>
<tr><td>Fox Hills Sandstone</td><td colspan="2">Fox Hills Sandstone</td><td colspan="2">Fox Hills Sandstone</td></tr>
<tr><td>Pierre Shale</td><td colspan="2">Pierre Shale</td><td colspan="2">Pierre Shale</td></tr>
<tr><td>Niobrara Formation</td><td colspan="2">Niobrara Formation</td><td colspan="2">Niobrara Formation</td></tr>
<tr><td>Carlile Shale</td><td>Carlile Shale</td><td rowspan="3">Benton Shale</td><td>Carlile Shale</td><td rowspan="3">Benton Shale</td></tr>
<tr><td>Greenhorn Limestone</td><td>Greenhorn Limestone</td><td>Greenhorn Limestone</td></tr>
<tr><td>Graneros Shale</td><td>Graneros Shale</td><td>Graneros Shale</td></tr>
<tr><td>Lower</td><td>Dakota Group</td><td colspan="2">Dakota Group</td><td colspan="2">Dakota Group</td></tr>
</table>

[1]Data published after preparation of this part of the report indicate that the lower member of the Dawson Arkose is no older than late Paleocene, the main body of the Dawson is of Eocene age, and the formation overlies the Denver Formation where both units are present (Soister, 1978, p. 227, fig. 2).

TABLE 1.—*Rock units in the Front Range Urban Corridor, Colorado*—Continued

ERATHEM	SYSTEM	SERIES	COLORADO SPRINGS–CASTLE ROCK AREA	GREATER DENVER AREA	BOULDER–FORT COLLINS–GREELEY AREA
MESOZOIC	JURASSIC	Upper	Morrison Formation	Morrison Formation	Morrison Formation
			Ralston Creek Formation	Ralston Creek Formation	Sundance Formation: Windy Hill Sandstone, Pine Butte and Canyon Springs Members
		Middle			
		Lower			
	TRIASSIC	Upper			Jelm Formation
			Lykins Formation	Lykins Formation	Lykins Formation
PALEOZOIC	PERMIAN		Lyons Sandstone	Lyons Sandstone	Lyons Sandstone
					Satanka Formation
			Fountain Formation	Fountain Formation	Ingleside Formation
	PENNSYLVANIAN				Fountain Formation
	MISSISSIPPIAN		Leadville Limestone		
	DEVONIAN		Williams Canyon Limestone		
	SILURIAN				
	ORDOVICIAN	Upper			
		Middle	Harding Sandstone		
		Lower	Manitou Limestone		
	CAMBRIAN	Upper	Peerless Dolomite		
			Sawatch Sandstone		
PRECAMBRIAN (Proterozoic Z, Y, and X)			Pikes Peak Granite, Silver Plume Quartz Monzonite, Boulder Creek Granodiorite, and associated intrusive masses; pegmatite lenses, dikes, and irregular bodies related to major intrusives Metamorphic rocks, including gneiss, schist, quartzite, amphibolite, hornblendite, and others		

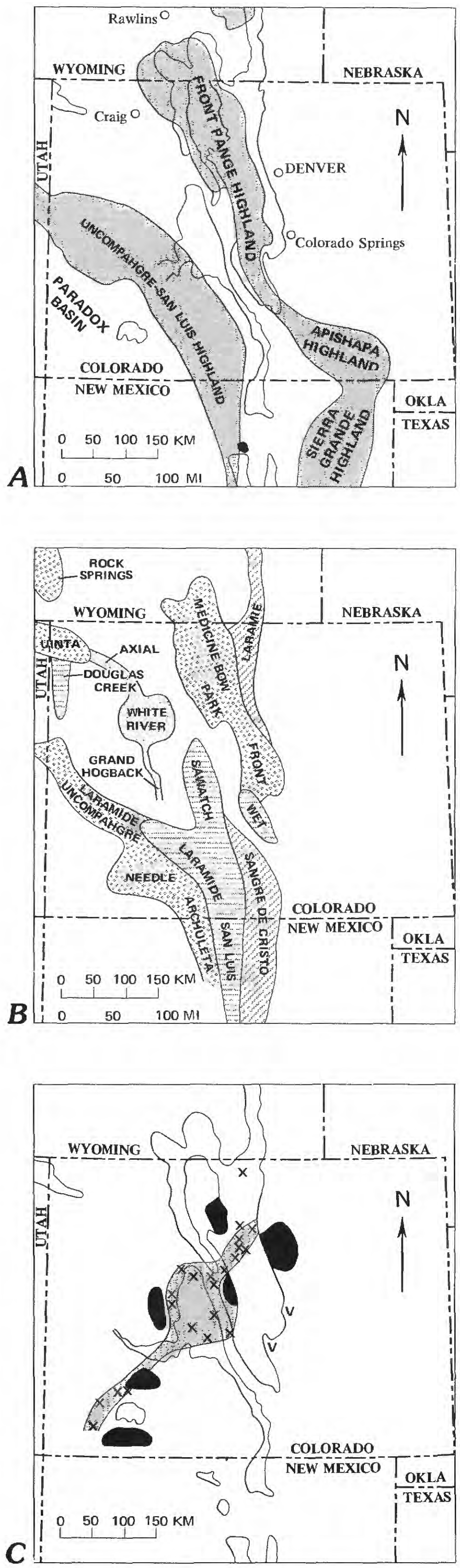


FIGURE 5.—Maps showing late Paleozoic and Laramide uplifts in the Southern Rocky Mountains. From Tweto, 1975, p. 5, 22, 28; courtesy, The Geological Society of America, 1975. A. Late Paleozoic uplifts (shaded) of ancestral Rocky Mountains (modified from Mallory, 1960, 1967). Outlines of main bodies of Precambrian rocks as now exposed shown for reference. B. Major Laramide uplifts classified according to time of first rise. Horizontal rules, Cretaceous, older than 75 m.y.; coarse dots, Cretaceous, 70 to 65 m.y.; diagonal rules, Paleocene; fine dots, Eocene. C. Laramide igneous and mineral belts. X, intrusive bodies of known or inferred Laramide age; solid black areas, andesitic sedimentary rocks and flows; V, minor occurrences of andesitic detritus; shaded strip, mineral belt as defined by Laramide intrusive bodies and productive mining districts. Outlines of main bodies of Precambrian rocks as now exposed shown for reference.

Upper Cambrian Sawatch Sandstone overlies Precambrian rocks discontinuously along the Rampart Range and grades upward into the dolomite, dolomitic sandstone, and shale of the Upper Cambrian Peerless Dolomite. In places outside the corridor, the Peerless grades up into Lower Ordovician Manitou Limestone, but near Colorado Springs the Peerless and Sawatch were beveled by erosion before the Manitou was deposited. The Manitou, therefore, cuts across the Peerless and Sawatch, and it lies on Precambrian rocks to the south (Berg, 1960, p. 11).

Near the southern boundary of the corridor, Harding Sandstone of Middle Ordovician age overlies the Manitou, but northward the Williams Canyon Limestone overlies the Manitou. The Williams Canyon is an unfossiliferous limestone that generally has been regarded as Mississippian, but it has been correlated by Baars (1972, p. 92) with rocks deposited in a Late Devonian sedimentary basin in western Colorado.

In the Colorado Springs-Manitou Springs area, the Williams Canyon Limestone is overlain by the Leadville Limestone of Mississippian age. The Leadville Limestone was the last formation deposited in the Front Range area before the uplift of the ancestral Rocky Mountains.

LATE PALEOZOIC AND EARLY MESOZOIC TIME

An increase in crustal unrest in the Southern Rocky Mountain region probably began in Late Mississippian time with regional uplift and withdrawal of the seas westward and southeastward. By Early Pennsylvanian time, the major structural elements of the ancestral Rocky Mountains (fig. 5) were defined but were not yet developed to their ultimate height or lateral extent. These elements were the ancestral Front Range highland (trending slightly more northwest than the present Front Range), the Apishapa highland to the south and southeast of the Front Range, the Uncompahgre highland southwest of the Apishapa, and the subsiding basins that bordered or separated these highlands (Mallory, 1975, p. 268–269; Wilson, 1975, p. 247, 251). The highlands provided most of the sediments that filled the basins to or above sea level in Pennsylvanian and Permian time. The older Paleozoic

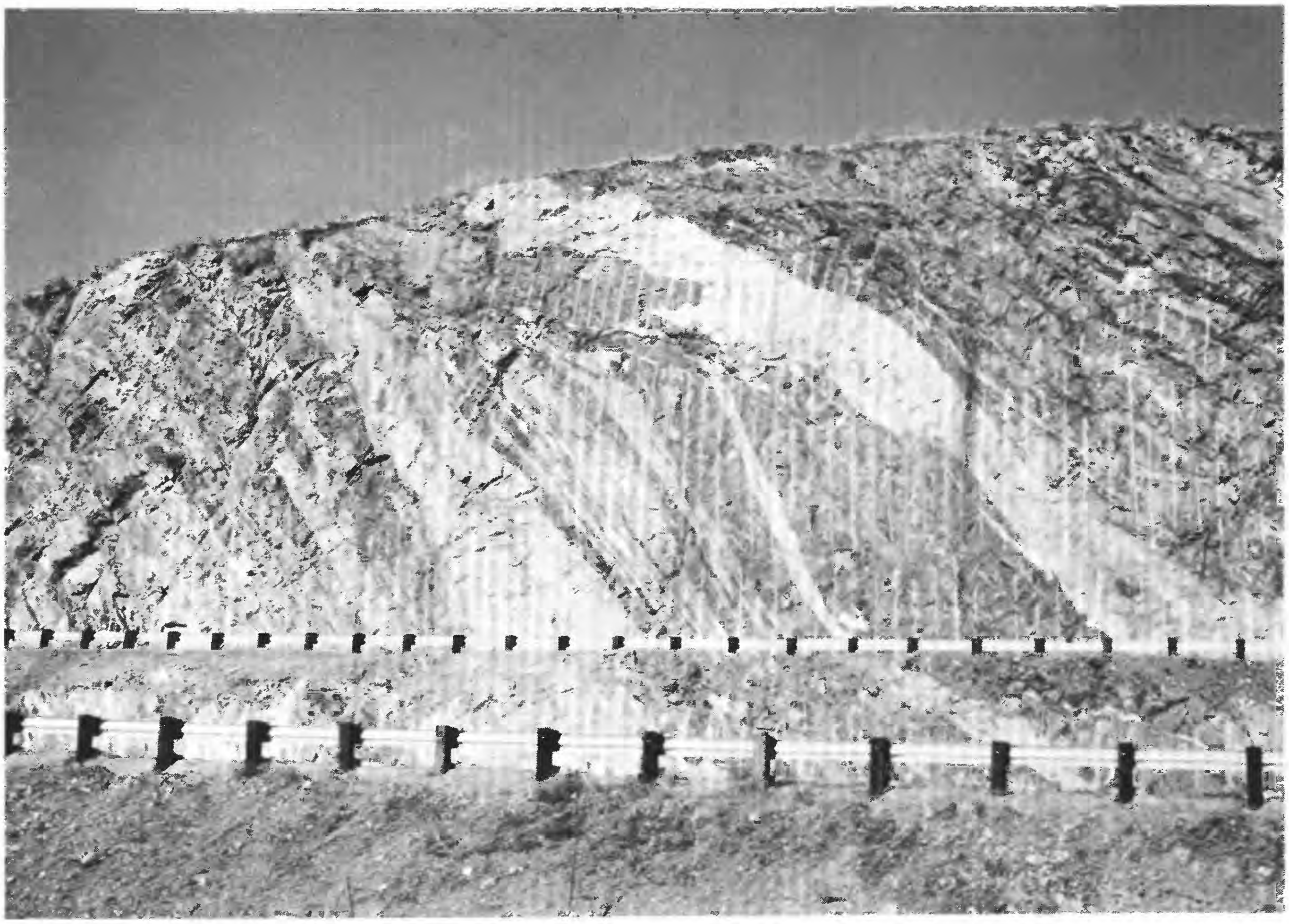


FIGURE 6.—Precambrian gneiss (darker layers) and pegmatite (lighter layers) exposed in a roadcut along Interstate 70 in foothills of the Front Range at Mount Vernon Canyon west of Denver. Long vertical drill-hole scars indicate that the cut was excavated by the presplit method, which is used in competent rock. Roadcuts provide the best exposures of the old Precambrian complex. November 1971.

rocks were removed from the highlands and the Precambrian rocks were deeply eroded. As mountain height and the supply of detritus were reduced, marine carbonate and saline deposits formed over wide areas, though not notably so in the Front Range Urban Corridor.

The geology of the Front Range Urban Corridor has been influenced mainly by the development and destruction of the northern and eastern ancestral Rocky Mountains. Early Pennsylvanian uplift in the northwestern Apishapa highland and to a lesser extent in the northern Front Range highland supplied mud and some arkosic sand to alluvial plains that stretched to a shallow sea in eastern Colorado (Wilson, 1975, p. 250-251). Uplift of the Front Range highland yielded coarse arkosic sediment, and downwarping of the adjoining eastern basin reached a maximum in Middle Pennsylvanian time. Thereafter, diminished crustal activity in Late Pennsylvanian through Permian, Triassic, and Jurassic time was interrupted only briefly by resurgent local uplift or regional warping. Erosion reduced both height and areal extent of the mountains until only isolated low hills remained above the levels of plain and sea.

Shorelines fluctuated widely throughout the late Paleozoic and early Mesozoic. At times, lagoons or bays of the eastern sea became saturated with calcium sulfate, owing to circulation barriers, and anhydritic mud and some purer lenses of anhydrite (later altered to gypsum) were deposited. The many changes in the landscape are recorded by disconformities; more than a dozen erosion surfaces are recognized in the Southern Rocky Mountain region within the Middle Triassic to Upper Jurassic rock sequences alone (G. N. Pipiringos, oral commun., 1978).

Within the Front Range Urban Corridor, more than 1,500 m of arkosic red beds, the Fountain Formation (Pennsylvanian and Permian; Mudge, 1967; Wilson,

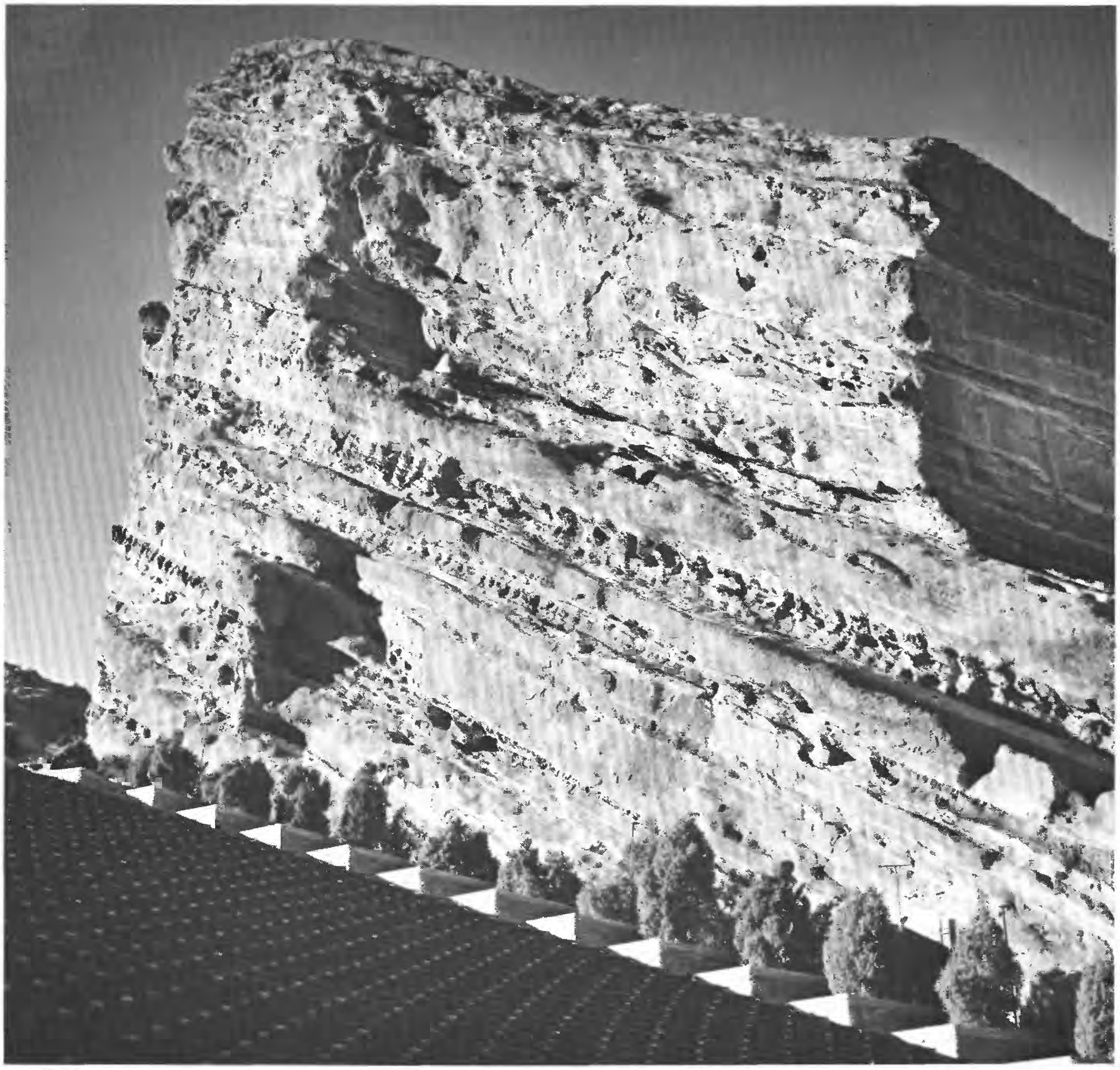


FIGURE 7.—Fountain Formation at Red Rocks Park, Jefferson County, 1965. Irregularly bedded arkosic sandstone and conglomerate are interbedded with finer grained ferruginous sandstone (darker layers). These rocks formed from sediments that were derived from the ancestral Rocky Mountains and accumulated on an alluvial plain in Pennsylvanian and Permian time. Photograph by J. R. Stacy, U.S. Geological Survey.

1975), accumulated near Colorado Springs on alluvial fans at the mountain front where deposition kept pace with or exceeded subsidence. Streams carrying sand, pebbles and cobbles meandered across muddy flood plains (fig. 7). The Fountain Formation thinned northward within the corridor and intertongued with a fluvial or marginal-marine sand of the Ingleside Formation (Lower Permian; Maughan and Wilson, 1960, p. 37).

The Lyons Sandstone (Permian), about 100 m thick near Lyons, was deposited on the Fountain Formation between the highland to the west and the marine evaporite basins to the east. The formation covered much of this corridor area. In the north, all but the uppermost beds of the Lyons Sandstone graded into the estuarine or tidal-flat sand and silty sand that became the lower part of the Satanka Formation (Maughan and Wilson, 1960, p. 37). Near Lyons, the light-colored, partly cross-bedded sandstones of the Lyons Sandstone have been interpreted as wind-drifted dunes interbedded with stream-laid sands (Walker and Harms, 1972, p. 279). Crossbedded sandstone and arkose in the Golden-Morrison area may have been deposited by streams partly within reach of tidewater (Weimer and Land, 1972a). Near Colorado Springs the Lyons—210 and 245 m thick in this area—grades up from massive red sandstone through arkose into white to red cross bedded sandstone (Grose, 1960, p. 190). The arkose resembles the Fountain Formation, but with local exceptions is finer grained than the Fountain. Gradual lowering of the ancestral Rocky Mountains by erosion reduced stream gradients and, consequently, diminished the ability of streams to carry coarse sediments to the sea.

The height of the source areas continued to lower and the average grain size of deposited material continued to decrease through Late Permian and into Early Triassic time. The Lykins Formation, which was deposited next, is more uniform laterally than are deposits in the Fountain and Lyons. Brick-red mudstone, fine-grained sandstone, and thin limestone and gypsum beds are products of coastal plain, shoreline, and partly evaporitic shallow marine environments (Weimer and Land, 1972a, p. 295–296; Van Horn, 1976, p. 13).

The corridor contains no rocks of Middle Triassic through Lower Jurassic age other than crossbedded sandstone of the Upper Triassic non-marine Jelm Formation, which is exposed from northeastern Boulder County into Wyoming (Pipiringos and O'Sullivan, 1976). The Jelm in the corridor area is believed to have been deposited when the northern part of the waning Front Range highland underwent minor uplift during Middle or Late Triassic time (M. R. Mudge, in McKee and others, 1959, p. 17). This event is suggested partly because the Jelm is coarser grained than the underlying Lykins and partly because it rests on a surface eroded into the Lykins. In late Paleozoic time the highland continued to erode elsewhere in the corridor, and ultimately the Jelm itself was partly removed.

The sea then returned from the north in a series of Middle Jurassic advances, partial retreats, and readvances. The crossbedded basal Canyon Springs Member of the Sundance Formation and a more massive younger Pine Butte Member were spread across the northern part of the Front Range Urban Corridor area. Near Boulder, the basal sandstone passes southward into the lower part of the Ralston Creek Formation, which probably accumulated near the shoreline (Pipiringos and O'Sullivan, 1976; G. N. Pipiringos, oral commun., 1978). No comprehensive study of the Ralston Creek Formation has been published. Many geologic reports, however, note that red and varicolored mudstones, thin sandstones and limestones, and gypsiferous beds of this formation crop out intermittently from Ralston Reservoir northwest of Denver to the southern border of the corridor and that the formation also occurs in the subsurface to the east.

As the sea again withdrew in Late Jurassic time, the Morrison Formation spread across the low interior of the continent, including the area of the Front Range Urban Corridor. Varicolored clayey mud, sand, fresh water lime mud, and volcanic ash from sources far to the west were deposited in lakes and streams. (See Oriel and Craig, 1960.)

PRESENT DISTRIBUTION OF UPPER PALEOZOIC TO MIDDLE MESOZOIC ROCKS

Today, upper Paleozoic to middle Mesozoic rocks are exposed mainly in the narrow hogback belt along the mountain front, but they underlie much of the Colorado Piedmont at depth. Most conspicuous is the Fountain Formation, seen in the maroon monument rocks of the Garden of the Gods west of Colorado Springs, at Perry Park and Roxborough Park south of Denver, in Red Rocks Park west of Denver, in The Flatirons at Boulder, and in less well known exposures throughout the length of the corridor. The lighter colored Lyons Sandstone also forms a locally conspicuous outcrop, but most of the other formations are poorly exposed in gently sloping hillsides or valley floors below the high hogback of the Dakota Group, described in the following paragraphs.

PRE-LARAMIDE, LATE MESOZOIC TIME

The last marine invasion of the continental interior spread south from the Arctic in late Mesozoic time. Early in the Cretaceous Period, it joined briefly with a sea extending northward from the Gulf of Mexico. A continuous seaway in Late Cretaceous time was finally drained by the Laramide uplift. The floor of this interior seaway subsided most deeply near its western margin in western Utah and eastern Nevada. Mountains rising to the west shed more than 3,000 m of sediment into the trough and kept the depositional surface above or near sea level, but a central zone of deeper water in western Colorado received relatively little sediment. Farther east, shallower water extended into the midcontinent on a broad shelf, and here limited

FIGURE 8.—Oscillatory ripple marks in upturned beds of the Kassler Sandstone Member of the South Platte Formation, Dakota Group, exposed in the wall of a claypit near Interstate 70, Jefferson County. Photographed in November 1974. The ripple marks were formed in shallow, standing water. Desiccation cracks and dinosaur tracks (fig. 9) elsewhere in the Kassler indicate ephemeral emergence and drying. The Kassler is the highly productive "J" sand in oil and gas fields of the Denver Basin.

deposition was often interrupted by temporary withdrawals of the water (fig. 8). Local upwarping and sagging of the sea floor caused many changes in the position of the shoreline and in the directions of sediment transport. Marine and nonmarine sediments intertongued repeatedly (Kauffman, 1977) as the shoreline shifted back and forth.

The Front Range Urban Corridor lay generally in the transitional hinge zone between the shallow-water eastern shelf and the deeper water zone to the west; but in the several stages of Cretaceous deposition, environments in the corridor ranged from alluvial to offshore marine. The Lower Cretaceous Dakota Group began to accumulate as lenticular channel sands and gravels and as alluvium on a flood plain (Lytle Formation). Sediment was supplied from the west or southwest. The overlying South Platte Formation (fig. 9) was deposited in coastal-plain channels, delta channels and bays, shallow marine waters, and on flood plains and tidal flats; the sea advanced toward the south or southwest (Weimer and Land, 1972b).

Marine detrital mud, lime mud, and sand accumulated in the corridor through much of the Late Cretaceous, and at times volcanic ash was introduced from far western sources. These deposits constitute the Graneros Shale (partly Lower Cretaceous), Greenhorn

Limestone, Carlile Shale, Niobrara Formation, and Pierre Shale. They have a combined maximum thickness of more than 3,000 m in the northern part of the corridor (Colton, 1978) and about half of that thickness in the south (Trimble and Machette, 1979a and b). In some sections of this report the name Benton Shale is used with reference to undifferentiated rocks of the Graneros Shale, Greenhorn Limestone, and Carlile Shale.

The many changes in the vertical sequence of Upper Cretaceous rocks in the corridor resulted from at least five major expansions and contractions of the seaway (Kauffman, 1977). Its final withdrawal was accompanied by a progressive eastward shift of a zone of shoreline sands, now the Fox Hills Sandstone, and, close behind the retreating strand, by the coal swamps and flood plains of the Laramie Formation (fig. 10). The Fox Hills and Laramie added another 150–400 m to the geologic section. The deposition of nonmarine sediments was associated with the draining of the sea and the beginning of the Laramide orogeny. In the corridor, the Laramie Formation represents a transition from pre-Laramide nonorogenic sedimentation and Laramide orogenic sedimentation.

PRESENT DISTRIBUTION OF PRE-LARAMIDE, UPPER MESOZOIC ROCKS

The upper sandstones of the Dakota Group form the most prominent of the major hogback ridges along the mountain front. Some ridges are 150–300 m high. Locally the Fort Hays Limestone Member of the Niobrara Formation sustains a lower ridge east of the Dakota, and sandstones in the Pierre Shale form ridges 30 m high or more in places between Boulder and Fort Collins. Pierre Shale is the bedrock in much of the corridor south and southeast of Colorado Springs and, together with the Fox Hills Sandstone and Laramie Formation, it underlies the northern third of the corridor east of the hogback belt. In most of the central part of the corridor these formations are concealed beneath younger rocks.

LATEST CRETACEOUS TO EARLY EOCENE TIME

Laramide mountain building began about 70 m.y. ago in central and western Colorado. About 67 m.y. the Front Range (fig. 5) began to rise along the trend of the late Paleozoic Front Range highland. The uplift nearly coincided with the present Front Range in the south, but to the north it diverged northwest from the trend of the present mountain front. The amount and type of uppermost Cretaceous and Paleocene sediments shed from the range suggest that rapid erosion kept the mountains from reaching the height of the present Front Range. Uplift in early to middle Eocene time steeply tilted the Paleocene and older sedimentary rocks along the mountain front south of Boulder, and steep reverse faults displaced the mountain flank. North of Boulder, the eastern part of the present Front Range—east of the rejuvenated late Paleozoic highland (fig. 5)—probably did not develop until Paleocene time. At that time, northwest-trending folds and reactivated faults of Precambrian origin began to raise a series of en echelon blocks along the present mountain front. In northward sequence, each block was offset northeast, creating the indentations that contrast with the smoother curve of the front farther south. (See Tweto, 1975, p. 25–26, 31–33; Epis and others, 1976, p. 323–324.)

Early Laramide crustal disturbance was accompanied by intrusive and extrusive igneous activity. This activity diminished in later Laramide time, but resumed in Oligocene time and persisted into the Miocene. During the Late Cretaceous and Tertiary, the first intrusive bodies invaded a zone, now called the

FIGURE 9.—Dinosaur footprint in the South Platte Formation of the Dakota Group at Alameda Parkway near Morrison. Print is about 44 cm long front to back. Sharp claw marks indicate a carnivorous dinosaur; it was walking on its toes, leaving no heel print. May 1968.

FIGURE 10.—Steeply dipping Fox Hills Sandstone exposed near Alameda Parkway on the south side of Green Mountain, Jefferson County. Person is at the Pierre Shale-Fox Hills Sandstone contact. Fox Hills Sandstone-Laramie Formation contact is at right. Photograph by J. R. Stacy, U.S. Geological Survey, 1965.

Colorado mineral belt, that extended from southwesternmost Colorado northeast across the Front Range to a point near Boulder. Many of Colorado's ore deposits are related to these intrusions. Volcanoes erupted within the Colorado mineral belt (Laramide mineral belt of Tweto, 1975, fig. 4) and in adjacent areas. The eruptions and rapid erosion of the rising mountains contributed sediments to lakes and streams over a broad area. (See Tweto, 1975, p. 21–25.)

As the area of Laramide uplift enlarged eastward in latest Cretaceous time, erosion of about 3,000 m of Upper Cretaceous Pierre Shale and older sedimentary rocks provided fine sand, silt, and clay to form the Laramie Formation east of the mountains (Tweto, 1975, p. 19–20). Coarser sediments, possibly brought from a source west of the mountains, were incorporated into the upper part of the Laramie in the southern part of the corridor. The coarse texture of the Dawson Arkose (Upper Cretaceous and Paleocene), which was laid down on the Laramie in much of the southern half of the corridor, records greater uplift and more intensive erosion of the mountains. Coarse arkosic sediment derived from the Pikes Peak Granite was deposited as conglomerate in the Dawson close to the present edge of the mountains. In the Denver area, the Arapahoe Formation graded southward into the lower part of the Dawson. The Arapahoe also contains conglomerate at its base and locally at higher levels (Van Horn, 1976). Both formations pass eastward into finer grained lenticular beds of sand, silt, and clay.

The Denver Formation (Upper Cretaceous and Paleocene) overlies the Arapahoe and intertongues with part of the Dawson. It is distinguished by its content of Precambrian detritus and Upper Cretaceous and Paleocene andesitic sediment, which was carried by streams from volcanic sources to the west (fig. 11). All traces of the volcanoes have since been eroded. The Dawson Arkose, which is partly a time equivalent but is generally nonvolcanic, reportedly contains one Cretaceous and one Paleocene zone of andesitic material near Colorado Springs. This material is thought to have come from a volcanic source west of South Park and about 120 km west of Colorado Springs (Scott and others, 1976, p. 324). Recent data indicate that the upper part of the Dawson is of Eocene age (Soister, 1978). Dark-colored lava flows (Table Mountain Shoshonite) in the Denver Formation of North and South Table Mountains at Golden are believed to have come from vents associated with intrusive masses of similar rock between Golden and Lyons. The most probable sources were the Ralston Reservoir intrusive (Larson and Hoblitt, 1973, p. 4) or one or more of the smaller monzonite intrusives just northwest of North Table Mountain (Van Horn, 1976, p. 53).

South of Golden at Green Mountain, the Denver Formation is overlain by the Green Mountain Conglomerate of Paleocene age, which probably is equivalent to beds in the Dawson Arkose. The Arapahoe and Denver Formations and Green Mountain Conglomerate may never have been deposited in the corridor north of Boulder, or they may have been eroded from there during late Paleocene-early Eocene uplift (Tweto, 1975, p. 33).

MIDDLE AND LATE EOCENE TIME

Laramide uplift of the Front Range declined sharply after early or middle Eocene time, when igneous activity also diminished. But erosion continuing through late Eocene time, without compensating uplift, leveled off a broad, low, east-sloping plain known as the late Eocene erosion surface. Remnant hills a few hundred meters high and river channels added character to the scene. Locally, the plain merged with a much older pre-Mesozoic or pre-Paleozoic surface exhumed by Eocene erosion. Paleobotanical evidence indicates that the regional altitude was no more than 900 m above sea level. Alluvium accumulated on the plain locally and in stream valleys or downfaulted blocks below the general level of the surface (Scott, 1975, p. 230–231; Epis and others, 1976, p. 324–328).

In the Front Range Urban Corridor, the late Eocene erosion surface extended across the Front Range eastward onto the Great Plains without much of a break in slope at the mountain front. The broad summit of the Rampart Range is the most extensive approximation of the late Eocene surface remaining within the corridor. There the surface may have been protected from erosion in Oligocene time by a cover of volcaniclastic rocks. In Miocene time, east-flowing streams were deflected by the rise of the Rampart

FIGURE 11.—Denver Formation exposed near Alameda Parkway in Lakewood, showing friable, unevenly bedded, clayey, volcaniclastic sandstone. Clayey sandstone such as this has a high shrink-swell potential. Gravel at top of outcrop is of Quaternary age. Photograph by J. R. Stacy, U.S. Geological Survey, 1965.

Range fault blocks. Later erosion stripped off the Oligocene deposits except from a few depressions in the old surface. Erosion cut to a depth of a few tens of meters below the Eocene surface in many places, but the general form of the surface is well represented by the Rampart summit. Parts of the old surface remain to the north also, beyond the South Platte River, but much of it there has been destroyed by continued erosion (Scott, 1975, p. 232–233.)

OLIGOCENE TIME

The volcanic quiescence that followed the Laramide uplift in Eocene time ended in early Oligocene time with eruptions in the southern part of the present Sawatch Range (about 125 km west of the southern part of the corridor). Silicic ash flows of the Wall Mountain Tuff spread eastward and northeastward from South Park toward and beyond Castle Rock. Volcanic eruptions continued into Miocene time, diverting and damming streams in some areas and locally impounding large lakes (see Epis and others, 1976, p. 328).

Within the Front Range Urban Corridor, the Wall Mountain Tuff is overlain by the Castle Rock Conglomerate. The Wall Mountain Tuff flowed down the late Eocene slope, following stream channels and, in places, overtopping interstream areas. West of Castle

Rock, its northeastward path was at least 8-9 km wide and its maximum thickness was about 15 m. Before the end of early Oligocene time, the Wall Mountain Tuff was channeled by streams and buried by the Castle Rock Conglomerate, a mixture of volcaniclastic debris and boulders, cobbles, and finer grained material from Precambrian sources (Izett and others, 1969; Epis and others, 1976; Trimble and Machette, 1979a, b).

PRESENT DISTRIBUTION OF THE OLIGOCENE ROCKS

Remnants of the Castle Rock Conglomerate crop out irregularly in a large area in southeastern Douglas County and in isolated small mesas and buttes elsewhere in the county. In a small area south of Castle Rock and elsewhere on some mesas and buttes, the conglomerate rests on the Wall Mountain Tuff. On some buttes, however, the Wall Mountain is the cap rock and the Castle Rock Conglomerate is absent.

MIOCENE, PLIOCENE, AND QUATERNARY TIME

The Southern Rocky Mountains began to rise to their present heights early in Miocene time. Uplift increased in the Pliocene but decreased in the Pleistocene and probably the Holocene. Block faulting was the major mechanism, and differential uplift of adjacent mountain and valley blocks in parts of the mountain region amounted to several hundreds to several thousands of meters. Some of the movement was along reactivated faults of Laramide, Paleozoic, or Precambrian origin. In this process, the Eocene erosion surface was fragmented, many stream courses were interrupted and deflected by fault scarps, and valleys were choked with detritus from blocks that eroded as they rose. Volcanism and intrusive activity associated with the Colorado mineral belt persisted into Miocene time. In Pleistocene time, a climate cooler and wetter than that of the Tertiary brought valley glaciers to the high mountains and extensive destruction of the Eocene erosion surface. (See Epis and others, 1976, p. 334; Scott, 1975; Soister, 1967; Tweto, 1975, p. 22.)

In Miocene time streams that had flowed across the rising Rampart Range were deflected by the scarps of major faults, such as the Ute Pass fault. North of the South Platte River, however, streams such as Clear Creek were able to maintain courses that probably had been established in Laramide time (Scott, 1975, p. 233). Patches of high gravels along the canyon walls of Clear Creek and other large Front Range streams are thought to be Miocene valley fills that escaped erosion during Pliocene and Quaternary uplift. By late Quaternary time, Clear Creek Canyon and other canyons were eroded to depths of 400-500 m below the Eocene erosion surface. (See Scott, 1975, p. 240-241.)

As the rate of uplift declined in latest Pliocene or early Pleistocene time, so did the rate of erosion along the streams flowing eastward from the Front Range. Streams that emerged from canyons at the mountain front alternately eroded and aggraded. Pediments were cut on bedrock and, in times of reduced stream activity, gravels accumulated on the pediments. Each pediment and its gravel cap were lower and less extensive than the preceding ones. The principal pediment gravels, from highest to lowest, have been named Nussbaum, Rocky Flats, Verdos, and Slocum Alluviums. These gravels are best preserved on nearly flat-topped, dissected benches or mesas along or near the mountain front or just east of the hogbacks in the bench-and-valley uplands section of the Colorado Piedmont. Alternating deposition and partial erosion, without pediment cutting, formed three or more terraces in the piedmont valleys of the corridor at levels between the lowest pediment gravels and the present streams. The main terrace deposits, in descending order, are Louviers Alluvium, Broadway Alluvium, and Holocene alluvium (in part called Piney Creek Alluvium). The alternate (and perhaps partly simultaneous) erosion and deposition that produced pediments, terraces, and their gravel caps may have been responses to cyclic climatic change, intermittent uplift, or both. (See Hunt, 1954, p. 113; Scott, 1975, p. 242-244.) The pediment and terrace alluviums probably correlate in part with cycles of Pleistocene glaciation in the higher mountains west of the corridor.

The landscape of the Front Range Urban Corridor is still changing. Streams are eroding, transporting, and redepositing sediment. Silt and clay are being carried east beyond the corridor, even to the Gulf of Mexico. Frost action, interstitial water, and the force of gravity move weathered rock slowly down slopes, locally causing landslides. Winds are agents of erosion and deposition. Strong northwest winds have carried sand and silt across much of the corridor north and east of Denver and northeast of Colorado Springs. Most of the sand has come from flood plains on the Colorado Piedmont. Large stabilized dune fields extend south from Greeley to Brighton. Some dunes have been reactivated locally in blowouts northeast of Denver. In the northern part of the corridor, shallow basins scooped out by the wind now contain lakes or reservoirs. Northeast of Colorado Springs, dune sand is being extracted commercially.

GEOLOGIC STRUCTURE SUMMARY

GENERAL SETTING

Two major features dominate the geologic structure of the Front Range Urban Corridor—the Front Range uplift on the west and the Denver Basin on the east

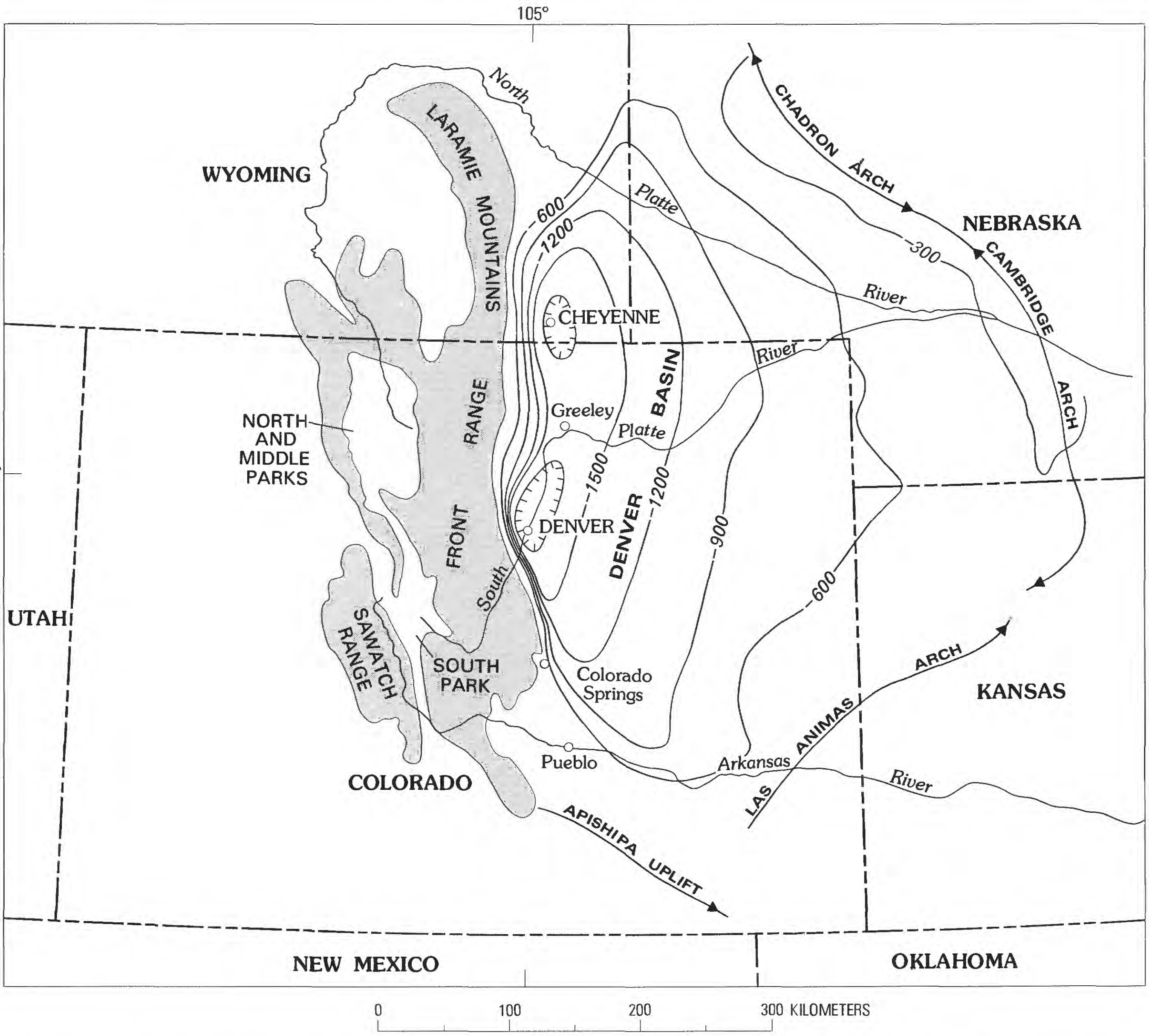


FIGURE 12.—Sketch map showing the Denver Basin (contoured in hundreds of meters on the top of the Precambrian rocks) and adjacent mountain ranges and uplifts. Shading indicates outcropping Precambrian rocks. Western Colorado mountains are not shown. Generalized from Cohee and others, 1961.

(fig. 12). These features are regional in size and extend far beyond the limits of the urban corridor. The Front Range, both as a mountain range and as a structural feature, is about 300 km long north to south and is about 40–65 km wide. It extends from the Canon City area on the south to about the Wyoming State line on the north. Including the Laramie Mountains, a northern extension in Wyoming, the Front Range is about 480 km long.

Structurally and topographically, the limits of the Front Range are clearly marked. The Denver Basin, on the other hand, is less sharply outlined except on the west where it meets the mountains. The basin is at least 560 km long north to south and is at least 420 km across. From its deepest part near Denver, it extends north into Wyoming and Nebraska, east into Nebraska and Kansas, and south to the Apishapa uplift south of Pueblo, Colo.

THE FRONT RANGE

A general outline of Front Range structure is provided here for a better understanding of the geologic framework of the Front Range Urban Corridor. The complex geologic structure of the range could be fully described only in a monographic treatise beyond the scope of this report. The Front Range uplift is a broad, flat-topped anticline. Tilted sedimentary rocks form a belt of hogbacks on the east flank of the range. Erosion has removed these rocks from the crestal part of the fold and, in the process, has deeply exposed the complex Precambrian core of the range.

The boundary zone between the Front Range uplift and the Denver Basin is a steep monocline—the hogback belt—along which the sedimentary rocks commonly are tilted 25°–45°; in places the rocks are much steeper or are even overturned, especially along faults. Dips are much flatter within the basin. The boundary zone is fractured in many places by high-angle reverse faults that dip westward beneath the mountain flank. They include the Golden, Jarre Creek, Rampart Range, and Ute Pass faults. Some workers have concluded that the faults diminish in dip surfaceward and in places flatten to rather low angles, although the evidence is not generally compelling.

Most investigators believe that the Front Range was elevated in Laramide time by essentially vertical uplift and that the mountain flanks and border faults coincide with zones of deep-seated, high-angle fractures in the basement. Van Horn (1976, p. 97) summarized evidence for steep fracturing along the Golden fault. Berg (1962, p. 2025) concluded that the overturned limb of the monocline near Golden is the principal mountain-flank structure and that the Golden fault cutting the monocline is but a secondary feature. Total displacements by faulting and monoclinal folding are measured in thousands of meters. Stratigraphic offsets may be much less. Some of the faults were reactivated by mountain uplift in early Miocene to early Pliocene time (Taylor, 1975, p. 224). This uplift gave the range much of its present configuration.

Several folds are present along the mountain-basin boundary, particularly in the northern part of the Front Range Urban Corridor (fig. 13). Some of these folds pass downward or laterally into faults. (For example, see Hunter, 1955; Boos and Boos, 1957, figs. 4–7, 13; Scott and Cobban, 1965; Braddock and others, 1970; Colton, 1978.)

The interior of the Front Range is broken by countless faults that vary greatly in size, orientation, and attitude (fig. 14). On the east flank of the uplift, but extending 30 km or more back into the mountains, is a belt of en echelon fractures that trend northwest to north-northwest (Tweto, 1976; Bryant and others, 1978). This belt is best defined in the middle part of the range where, because of brecciation and gouge zones, it exerts influence on the drainage and topography. The fractures originated in Precambrian time and probably predate the Pikes Peak batholith, but they have had recurrent movement at least through Laramide time (Lovering and Goddard, 1950, p. 79; Boos and Boos, 1957, p. 2638; Tweto and Sims, 1963, p. 997, 1001; Tweto, 1977, p. 12). Many of these faults extend from the uplift through the hogback belt, but most die out rapidly in the Denver Basin within a kilometer or less of the mountain front.

Front Range structure began to evolve in Precambrian time and grew progressively more complicated with repeated tectonic and magmatic events. Severe deformation of a thick sequence of already metamorphosed sedimentary/volcanic rocks about 1.75 to 1.70 b.y. ago was accompanied by high-grade metamorphism and plutonic activity. This episode brought the gneissic and schistose rock essentially to its present form (Hedge and others, 1967, p. 551; Peterman and others, 1968, p. 2277). These metamorphic rocks are intricately folded and strongly foliated, and the fold directions and foliation trends vary widely. The dominant trends, however, are west to northwest, and steep dips predominate.

Batholiths and smaller plutons of the Boulder Creek Granodiorite were intruded widely in the Southern Rocky Mountains 1.75–1.70 b.y. ago, modifying earlier structures. Subsequent structural events and features were then overprinted on these rocks. Widespread plutonic activity followed 1.45–1.39 b.y. ago (the Silver Plume and Sherman family of plutons), also accompanied by deformation, and again 1.04–0.98 b.y. ago (the Pikes Peak batholith) (Peterman and Hedge, 1968; Hutchinson, 1976, p. 74–75).

Structural modifications continued through Phanerozoic time, essentially to the present. The rise of the ancestral Front Range in Early Pennsylvanian time drastically altered sedimentation patterns across the region and set the stage for the Laramide events to come (p. 12). Laramide uplift was accompanied by igneous intrusion and volcanic activity. Stocks and smaller plutons rose through the core of the Front Range, and lavas flowed out on the surface. Dikes and sills intruded the east flank of the range in a discontinuous belt from Lyons on the north to Green Mountain on the south.

Present structural patterns were broadly defined by the time of the Laramide orogeny, when the buried worn-down roots of the Pennsylvanian mountains were re-elevated (Tweto, 1975, p. 6). The mountains as we know them today, however, really took form during Neogene time (Taylor, 1975), that is, the latter part of the Cenozoic Era. Erosion had truncated the Laramide structure of the Front Range by late Eocene time (Epis and Chapin, 1975, p. 46), and remnants of that erosion surface are still well preserved in many places along the west border of the Front Range Urban Corridor. Starting in early Miocene time, the present landscape began to take form as the Eocene erosion surface was displaced both up and down along faults. In places, movement on faults continued into the Quaternary

FIGURE 13.—Aerial view of the Big Thompson anticline near Loveland; a subordinate fold on the east flank of the Front Range, showing the eroded core of Precambrian crystalline rocks (Milner Mountain) and the sedimentary sequence of the fold. West is at the top of the photo. Faulting has partly deleted beds from the west limb of the fold. The area shown is about 12 1/2 km across. p€, Precambrian rocks; pIPf, Fountain Formation; Pi, Ingleside Formation; Ps, Satanka Formation; Ply, Lyons Sandstone; TRpl, Lykins Formation; JTRj, Jelm Formation; Jm, Morrison Formation; Kd, Dakota Group; Kb, Benton Shale (equivalent to Graneros Shale, Greenhorn Limestone, and Carlile Shale); Kn, Niobrara Formation; Kp, Pierre Shale. High-altitude aerial photograph by U.S. National Aeronautics and Space Administration, February 9, 1970.

(Scott, 1970; Kirkham, 1977). Earthquake epicenters along certain faults, such as the Golden fault and the Rampart Range fault, suggest that intermittent movement is still in progress (Simon, 1969).

DENVER BASIN

Because of its long history of oil and gas production and its high potential for further development, the Denver Basin has received much geological and geophysical attention. The published literature is voluminous, but only selected papers are cited here.

The Denver Basin is compound in that it has two widely separated structural lows—one centered near Denver and one near Cheyenne, Wyo. (fig. 12)—with at least 450 m of structural relief between them. The two parts, sometimes referred to as the Colorado part and the Wyoming or Julesburg part of the Denver Basin, are separated by a broad structural ridge trending east from about Loveland or Fort Collins toward Greeley, Colo. The following remarks apply to the Colorado part of the basin only.

A steep, partly overturned west limb and a very gently sloping east limb make the basin strongly asymmetrical (fig. 15), and its axis or trough line, therefore, (fig. 12) is much closer to the west border of the basin than to the east. Contours drawn on the surface of the crystalline basement (MacLachlan and Kleinkopf, 1969, pl. 1) indicate that the basin axis at that horizon is about 13 km from the mountains and the low point of the basin is near Castle Rock. At that point, the Precambrian surface is more than 2,300 m below sea level. Inasmuch as the basin rim on the Precambrian, southeast from Castle Rock, is less than 600 m below sea level, the enclosed negative relief on the Precambrian is more than 1,700 m. On the west, about 6,600 m of structural relief exists between the crest of the Front Range and the deepest part of the basin (Anderman and Ackman, 1963, p. 170).

At successively higher stratigraphic horizons, the axis of the basin shifts eastward from its position on the Precambrian surface. On the Laramie-Fox Hills

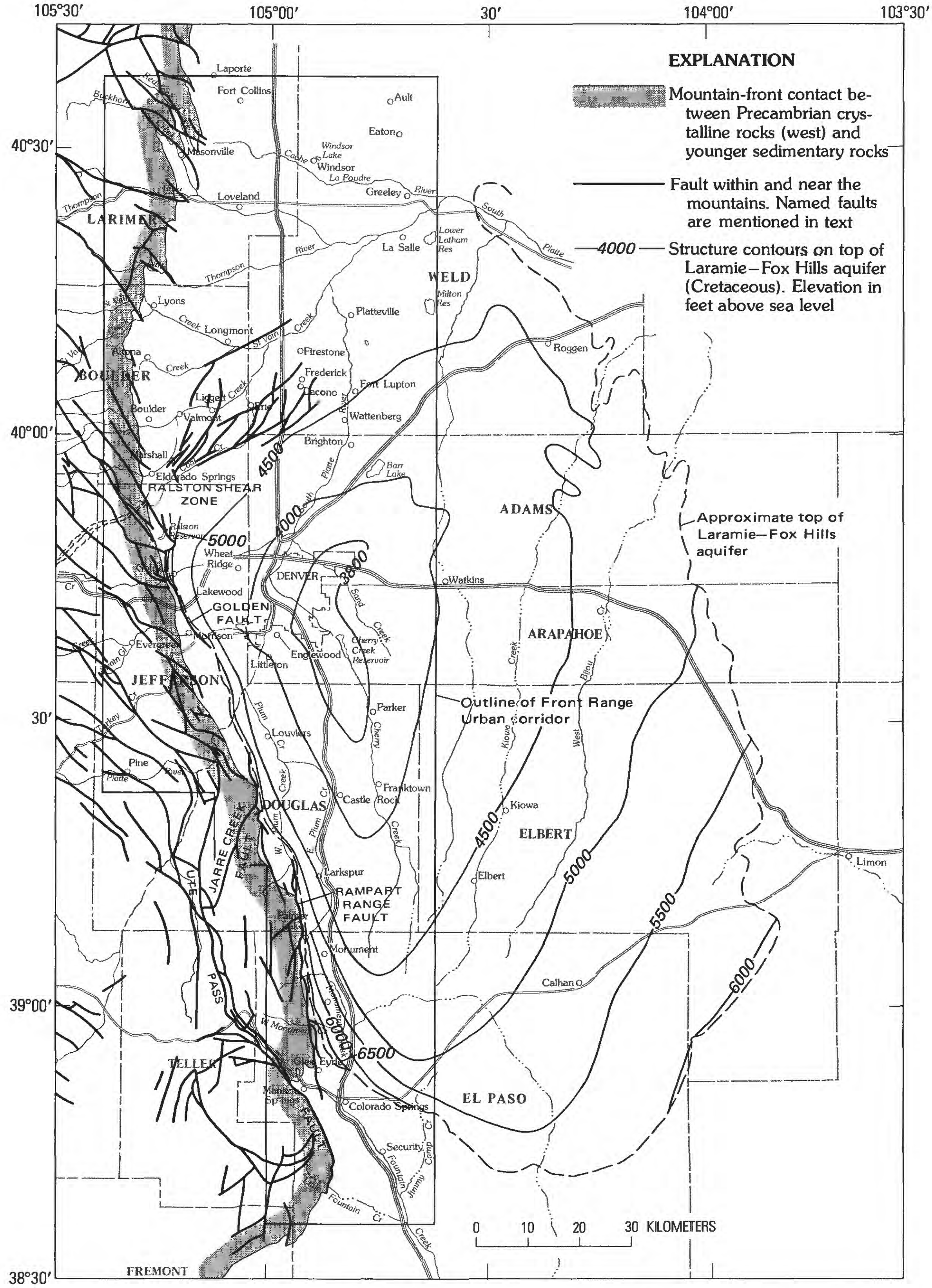


FIGURE 14.—Map showing selected structural features in and near the Front Range Urban Corridor. Modified from Tweto (1976), and Romero and Hampton (1972).

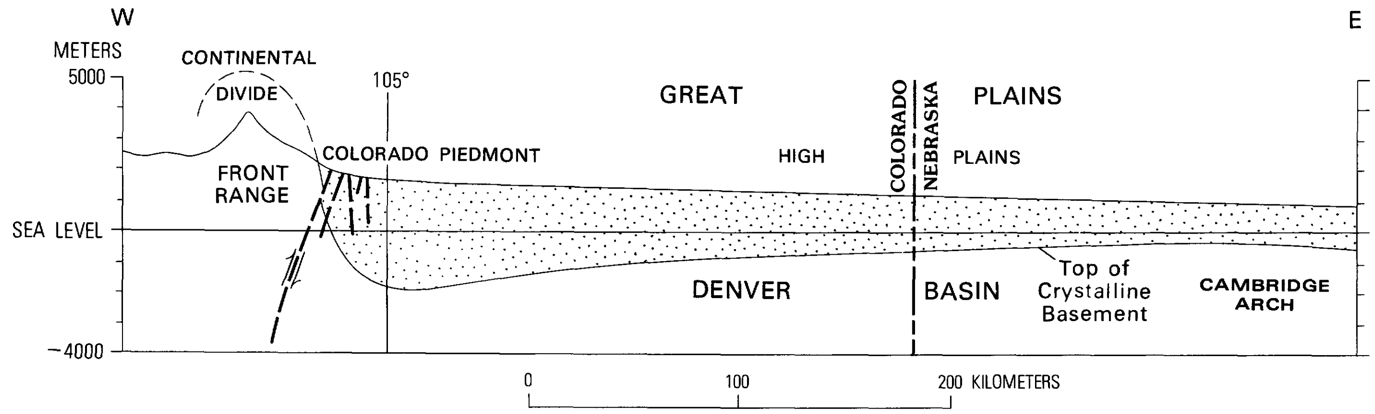


FIGURE 15.—Schematic section along the 40th parallel showing the asymmetry of the Denver Basin and its relation to the Front Range. Sedimentary rocks are indicated by stippling. Vertical scale is greatly exaggerated. Dashed lines are faults.

aquifer (Cretaceous), the axis is about 25 km east of the mountain front, and the low point of the basin is beneath Cherry Creek Reservoir, about 35-40 km north of Castle Rock.

SUBORDINATE FOLDING IN THE DENVER BASIN

The general simplicity of the Denver Basin is modified by subordinate folds and faults. Small anticlines are numerous in the northern part of the Colorado part of the basin, and many of them yield petroleum. Anticlinal noses and structural terraces are common also. Several of these noses plunge diagonally southeastward from the Front Range uplift. Some of them have local closures in Paleozoic or Mesozoic rocks, and some are breached by erosion to their Precambrian cores (for example, see Hunter, 1955; Braddock and others, 1970, and fig. 13).

Structure contours on a datum in the Fox Hills Sandstone-Pierre Shale transition zone suggest little likelihood of subsidiary folding in the basin southeast of a line from Boulder Creek to the South Platte River near Greeley (Romero, 1976, p. 5). Romero's map (pl. 5) shows one local closure at that horizon 18 km southeast of Greeley, however.

FAULTS IN THE DENVER BASIN

Tweto (1975, p. 19) has shown that the east limb of the Denver Basin began to form as part of the regional depositional basin of the Pierre Shale in Late Cretaceous (Montana) time. Initially, the axis of this depositional basin was in western Colorado, far to the west of the Front Range. The steep west limb of the present Denver Basin formed later, during the Laramide uplift of the Front Range. In this process, the west limb was deformed and faulted along the new basin margin at the mountain front; deformation of the east limb was minimal. Eastward from the west margin of the basin, faults are uncommon except in a zone about 18 km wide that trends northeast about 40 km from Rocky Flats past Firestone, Frederick, and Dacono.

Natural exposures of this fault zone are generally poor, except in a few localities. Individual faults are documented mostly by displacements in coal mines or by seismic profiles and well logs (Spencer, 1961; Davis, 1974, p. 10). Most of the faults trend northeast to north-northeast, but some trend north to northwesterly (Spencer, 1961; Colton and Lowry, 1973; Trimble, 1975; Colton, 1978). In general, they define a series of horsts and grabens, with displacements of as much of 150 m, but mostly less (Spencer, 1961). Spencer (1961) suggested that the faults might be related to reactivation of the northeast-trending Ralston shear zone, which is a structure of Precambrian age in the adjacent Front Range (Lovering and Goddard, 1950, pl. 1, 2). Weimer (1973, p. 53; 1976, p. 214) and Davis (1974, p. 52; Davis and Weimer, 1976, p. 280) ascribed the displacements to growth faulting within delta-plain unconsolidated sediments in Late Cretaceous time, controlled by recurrent movements on deep-seated basement faults. The faults appear to have been active during deposition of the Pierre Shale, Fox Hills Sandstone, and Laramie Formation, inasmuch as these stratigraphic intervals are reportedly thicker in the grabens than on the horsts.

URBAN MINERAL RESOURCES

The term "urban mineral resources," as used here, means those industrial mineral products extracted in or near the urban area primarily for use within the area. As commonly defined by the extractive industry, these products include gravel, sand, crushed stone, riprap, clay (for brick, tile, and sewer pipe), and to a lesser extent dimension stone, limestone for varied purposes, and earth fill. Products that might be incidentally extracted from within an urban area but not necessarily for local use, such as coal, natural gas, and petroleum, are not included here but are discussed in later sections of this report.

Like all other metropolitan areas, Denver and its satellite towns require large quantities of industrial mineral products to sustain growth and fill recurring needs. Most of these products are consumed in new construction and in maintaining and repairing existing facilities. In the rapidly expanding residential communities of the Front Range Urban Corridor enormous quantities of material are consumed by new growth. These products are used in the buildings, houses, streets, parking lots, drainage works, and so on that make up the physical framework of the community.

All are high-consumption, low-unit-value products whose price to the consumer depends greatly on haulage distance to the market. To be competitive, they must be obtained close at hand, often within the metropolitan area itself. Ironically, urban growth, which creates the demand and consumes the products, sometimes curtails production by preempting the unextracted resources for other land uses.

Groups along the Front Range have successfully prevented the extraction of industrial mineral products from some parts of the corridor, citing increased industrial traffic, air pollution, and reduced visual amenity as neighborhood concerns. Proper balance is being sought between demand for raw materials and other community wants and desires. At that point, the problem of supply and demand for urban mineral resources leaves the field of earth science and enters the socioeconomic political arena.

Local or nearby sources along the Front Range Urban Corridor fill all or most present needs for gravel, sand, crushed stone, riprap, clay for brick and tile, dimension stone, and earth fill. Supplies of limestone suitable for sugar refining, gypsum for agriculture and construction, and clay for high-quality refractory products are inadequate to fill the local demand, and these products are supplied in large part from outside sources (Crosby, 1976).

Data have been obtained from many published and unpublished sources. Publications that provide data on all or several of the nonmetallic resources of the corridor include Larrabee and others, (1947), Vanderwilt and others (1947), Argall (1949), Del Rio (1960), U.S. Geological Survey (1964), Colorado Bureau of Mines (1896 through 1965, 1966 through 1971), and Colorado Division of Mines (1972 through 1974) for Colorado; and U.S. Bureau of Mines (1965) and Brobst and Pratt (1973) for the United States as a whole. Unpublished information was obtained from files of public record of the Colorado Division of Mines and through the cooperation of Coors Porcelain Co., Denver Brick and Pipe Co., Environmental Lime Co., A. P. Greene Refractories Co., Robinson Brick and Tile Co., and Van Howe Ceramic Supply Co.

SOURCE AREAS

Along the urban corridor, the mountain area is a source of crushed rock, riprap, and small amounts of other nonmetallic mineral products such as gravel, sand, and earth-fill material. Locally, weathered bedrock, particularly granite grus, is used as road metal or aggregate for bituminous road surfacing.

The hogback belt flanking the mountains yields a wider range of materials: clay for brick, tile, sewer pipe, and other structural products; limestone for cement, crushed rock, and small amounts of dimension stone; sandstone for dimension stone, crushed rock, brick and cement additives, and landscape rock; and gypsum for use as a cement retardant (Crosby, 1976).

The Colorado Piedmont section of the Great Plains, where most of the population of the Front Range Urban Corridor is concentrated, contains extensive deposits of gravel, sand, sandstone, fine-grained igneous rock for use as crushed-rock aggregate, and clay and expandable shale—the latter usable for processing into lightweight (bloated) aggregate (Crosby, 1976).

GRAVEL AND SAND

The Front Range Urban Corridor contains a large resource of gravel and sand that could fill needs far into the future at present rates of consumption for use as aggregate, subgrade material, pervious fills, and other construction needs, provided that the resource is adequately conserved (Soule, 1974, p. 3, 18). Extensive areas underlain by high-quality gravel and sand, however, have been lost to production, especially in the Greater Denver Area, by urbanization across the resource or by zoning for nonextractive land use (fig. 16).

Estimates by Soule (1974, table 5) indicated that gravel and sand consumption in the Front Range Urban Corridor in 1974 equalled nearly 10 t (metric tons) per person per year. This rate was more than twice the national average and, in all probability, is higher now than it was then. Projected consumption between 1974 and the year 2000 is about 227 million metric tons, according to Soule (1974, table 5). Supplies in the Front Range area should fill that need if the resource is not lost to other land uses.

In recognition of the continuing need for gravel and sand, the Colorado Legislature in 1973 enacted a law (House Bill 1529) to prevent land uses that would interfere with the eventual extraction of commercial deposits of gravel and sand in the heavily urbanized

FIGURE 16.—Valley of Clear Creek (lower left to upper right) in Greater Denver Area, showing extent of gravel extraction as indicated by water-filled pits (black). Some pits have been backfilled and reclaimed. Although considerable gravel has been removed, much more remains and, in part, is still recoverable; however, some gravel deposits have been built upon. Area shown is 10.8 km across, left to right. North is at top. Interstate 25 trends north to south in right side of view. Interstate 70 is near bottom of view. High-altitude aerial photograph by U.S. National Aeronautics and Space Administration, February 9, 1970.

counties of the state. Most such counties are in the Front Range area. This law also contains provisions for the reclamation of exhausted open pits. The law does not apply to lands zoned for other uses prior to enactment.

Most high-quality gravel in the Front Range Urban Corridor is extracted from beneath the flood plains of the major streams or from adjacent low terraces (Ching, 1972, p. 20; Shelton, 1973; Colton and Fitch, 1974; Trimble and Fitch, 1974a; Schwochow and others, 1974, map). These gravel deposits are correlated with late Pleistocene (Bull Lake and Pinedale) glaciations in the nearby mountains. On the plains they are referred to as the Louviers and Broadway Alluviums (Hunt, 1954, p. 104; Scott, 1960, p. 1541). Some gravel and sand are still being deposited in the stream channels, largely through reworking of preexisting deposits.

Older gravel deposits of generally inferior quality cap higher terraces and pediments. These deposits are less sought after for commercial uses, except locally for road material, because the stones tend to be weathered or coated with calcium carbonate, or both, and because the deposits commonly contain unacceptably high proportions of interstitial calcium carbonate and silt. There are exceptions, and some deposits can be upgraded by crushing and washing.

Most excavations in or near valley bottoms extend down to or below the water table. Pits have been developed in the valleys of nearly all major streams of the area.

In general the lithologic character of a gravel deposit reflects rather closely the composition of parent bedrock upstream in the mountains (Colton and Fitch, 1974), which in turn affects the character and quality of the aggregate. Proportions of initial constituents vary, depending on durability of individual rock types and distances from source. Most of the gravel in the Colorado Springs area, for example, is derived from the adjacent Pikes Peak batholith, which is exposed in an area of 3,400 km^2 (Bryant and others, 1976, p. 17) and which yields gravel of generally inferior quality, owing to a high content of coarse-grained feldspar.

SOURCES OF GRAVEL AND SAND

The following descriptive summary is abstracted from Colton and Fitch (1974) and Trimble and Fitch (1974a, b). A potential source of gravel as defined by these authors contains 20 percent or more of granule- and pebble-size stones (smaller than 6.4 cm, but retained on a number 10 U.S. standard sieve (larger than 2 mm). Schwochow and others (1974) also provided brief summaries.

DEPOSITS UNDERLYING FLOOD PLAINS AND TERRACES

SOUTH PLATTE RIVER

Much of the flood plain of the South Platte River in the Denver area has been covered by urban development, and large volumes of high- quality gravel have been eliminated from use. Gravel has been much used upstream from the junction of Bear Creek, however, and downstream from the junction of Clear Creek, and there has been extensive early extraction along the South Platte between these tributaries. This gravel contains abundant stones of granite, quartz, and pegmatite, and lesser amounts of gneiss and schist.

Pebble counts (100 pebbles per count) of samples from the Fort Lupton, Platteville, and La Salle areas show that about 70 percent of the stones are granitic, 10 percent are gneiss, 10–20 percent are quartzite, and a few percent are sandstone, tuff, basalt, and gabbro. The composition of the stones changes little between Brighton and Greeley.

Deposits along the South Platte River flood plain and adjacent terraces are about 50 percent sand and 50 percent granules and small pebbles. The size distribution changes little between Brighton and Greeley. Well records indicate that coarser material may be present locally in the deeper parts of the deposits. Overburden is silty sand about 0.5–1 m thick. Windblown sand on the terraces is as much as 4.5 m thick locally but generally is only a meter or so.

In the Denver area, the deposits range from about 6–11 m in thickness, but in Brighton they are as much as 15 m thick. Farther north, thicknesses range from 15 m near Fort Lupton to 33 m near La Salle and Greeley.

CACHE LA POUDRE RIVER

The Cache La Poudre River valley has been the major source of gravel for Fort Collins, Windsor, and Greeley since the area was settled. The river and its tributaries drain mountain areas underlain mostly by gneiss, schist, and granite. Pebble counts from deposits west of Greeley indicate the gravel is 76–85 percent granitic rocks, 2–11 percent quartzite, 2–7 percent rhyodacite, and 3–4 percent gneiss.

The average diameter of the stones diminishes from about 2.5 cm just north of Fort Collins to less than 6 mm (millimeters) just northwest of Greeley.

Thickness of the gravel under the flood plain and terraces ranges from 6 m northwest of Fort Collins to 15 m northwest of Greeley. Drill records indicate greater thicknesses locally in buried channels (Ching, 1972; Shelton, 1973).

BIG THOMPSON RIVER

Much high-quality gravel and sand have been produced along the Big Thompson River south and east of Loveland. The Big Thompson and its tributaries Redstone Creek, Buckhorn Creek, and Little Thompson River drain mountainous areas of varied granitic rocks, pegmatite, quartzite, gneiss, and schist. In the hogback belt these streams—particularly Redstone and Buckhorn Creeks—drain extensive areas of sandstone, siltstone, and shale that tend to degrade the quality of the gravel. Little gravel has been produced, therefore, from these tributaries or, for the same reason, from the Little Thompson River.

Along the Big Thompson the gravel ranges from about 4 to 12 m in thickness, including generally less than a meter of sandy overburden.

ST. VRAIN CREEK

Deposits along St. Vrain Creek have been the source of gravel for the Longmont and Lyons areas. St. Vrain Creek and its tributaries drain mountain areas underlain largely by Silver Plume Granite. Pebble counts from deposits between Lyons and Longmont indicate that stones are 50–75 percent granitic rocks, 20–40 percent gneiss, 5–15 percent porphyry, 5–20 percent sandstone, and as much as 15 percent quartzite. Downstream, the percentage of granitic rocks decreases and the percentage of quartzite increases.

The average size of stones decreases downstream from the Lyons area to the confluence of St. Vrain Creek with Left Hand and Boulder Creeks. Near Lyons, the diameter of more than 50 percent of the stones is more than 2.5 cm, but in pits 8 km east of Longmont, the average diameter is 9.5 mm.

The thickness of the gravel is known locally along St. Vrain Creek. For example, test pits a few miles east of Lyons indicate as much as 6 m of gravel. Pits in the Longmont area indicate that the gravel is generally about 3 m thick but may be as much as 4.5 m locally.

LEFT HAND CREEK

Extensive deposits just east of the Front Range near Altona have been used for many years by the Boulder County Road Department and others, mostly for highway material. Sixty percent of the area drained by Left Hand Creek and its tributaries is underlain by Boulder Creek Granodiorite and Silver Plume Quartz Monzonite. Most of the remainder is metamorphic rock. Pebble counts from Table Mountain indicate that the stones are 30-50 percent granitic (including pegmatite), 15-35 percent sandstone, 10-55 percent quartzite, 5-40 percent gneiss or schist, and 5-10 percent fine-grained igneous rock.

At Altona, the gravel consists largely of boulder and cobble gravel. It decreases in size eastward to the vicinity of the confluence of Left Hand and St. Vrain Creeks where the average diameter of stones is 2.5 cm. The thickness is as much as 4.5 m near Altona and about 3 m near the confluence.

BOULDER CREEK

The deposits of Boulder Creek have been the major source of gravel for the Boulder area for many years. Boulder Creek and its tributaries (excluding South Boulder Creek, discussed separately) drain mountain areas largely underlain by Boulder Creek Granodiorite, biotite gneiss, some schist and quartzite, and a small area of Silver Plume Quartz Monzonite. Pebble counts near Boulder indicate that 50 percent of the stones are granite, granodiorite, or quartz monzonite, 20 percent are gneiss, and 15 percent are pegmatite. The percentage of granite, granodiorite, quartz monzonite, and pegmatite decreases downstream to 25 percent at the confluence with St. Vrain Creek; gneiss appears to be more durable, and its percentage doubles from 20 percent near the mountain front to 40 percent (20 km) downstream. Quartzite stones increase from 20 percent near the mountain front to 30 percent downstream.

The average size of stones decreases downstream from the foothills. Between Boulder and Liggett the average diameter is 32 mm, whereas near the confluence with St. Vrain Creek the average is 16 mm.

Generally, the deposits are thickest near the mountains, and commonly, but not everywhere, they also taper from the center of the flood plain toward the edge. Measured thicknesses are 4.5-7.6 m near Boulder, 3 m 0.8 km northwest of Liggett, and 2.4-37 m 3.2 km northwest or Erie.

SOUTH BOULDER CREEK

South Boulder Creek emerges from the mountains a few kilometers south of Boulder and flows northeastward. It drains a terrain of mostly Boulder Creek Granodiorite but partly Coal Creek Quartzite (Boos and Boos, 1934) these rock types predominate in the high-quality gravel of the valley fill. Granule and pebble gravel constitute about 50 percent of most deposits; sand and oversize gravel (cobbles and boulders) make up about 25 percent each.

COAL CREEK

Coal Creek flows from the mountains a few kilometers south of South Boulder Creek, and it, too, drains a terrain of Boulder Creek Granodiorite and Coal Creek Quartzite. Quartzite predominates. East of the mountains, Coal Creek has cut down through an older cobbly, bouldery (80 percent), quartzitic fan deposit into the underlying sedimentary bedrock. Cobbles and boulders, at least in large part recycled, therefore, constitute nearly half of the gravel along Coal Creek. Granules and pebbles form about a third, and the remainder is sand.

BEEBE DRAW

This ancient abandoned buried channel of the South Platte River along the east edge of the area contains thick deposits of sand and gravel. The channel is slightly more than 1.6 km wide. Well records and some test drilling by the U.S. Geological Survey (Smith and others, 1964) indicate that the deposits may be as much as 15 m thick. They are mantled by windblown sand and silt as much as 9 m thick under some dunes. The water table under Beebe Draw is near the surface.

Stone types from Beebe Draw are known only from terrace remnants 2 or 3 km south of Lower Latham Reservoir. Pebble counts indicate that 59-61 percent of the stones are granitic, 19-30 percent are quartzite, 4-7 percent are gneiss, and a few percent are sandstone, conglomerate, and porphyry. The character of the deposit at depth is unknown.

CLEAR CREEK

The valley of Clear Creek has been a major source of gravel for the Greater Denver Area for many years. Much of this deposit has been exhausted, but much high-quality gravel remains, although a large part of it has been preempted by urban growth. Clear Creek drains an area of mostly metamorphic and partly granitic rocks. Granitic rocks, however, constitute about 60–70 percent of the gravel and metamorphic rocks only 15–30 percent. This reversal of proportions between source area and gravel constituents probably reflects the difference in resistance to abrasion and disintegration between the granitic rocks and the metamorphic rocks. Near the mountain front and for several kilometers downstream, cobbles and boulders form about a third of the gravel, granule and pebble gravel about half, and sand and fines the remainder. The percentage of oversize material—cobbles and boulders—decreases downstream; near the confluence with the South Platte River, the gravel contains little oversize material. The amount of sand in the deposit is about constant. The thickness of the deposit is about 6–9 m, but it is only 2–3 m near the margins of the valley.

BEAR CREEK

Bear Creek and its tributary, Turkey Creek, drain an area of predominantly gneiss and schist intruded by large bodies of granitic rock. Less gravel has been extracted along Bear Creek than along either Clear Creek or the South Platte River. More than 25 percent of the gravel near the mountain front is cobbles and boulders, but the percentage decreases rapidly downstream and is negligible only a few miles from the mountain front. The granule and pebble fraction is consistently near 50 percent. The deposit commonly is 4.5–6 m thick.

PLUM CREEK

Plum Creek flows north into the South Platte River south of Denver. Its east fork heads on the north side of the South Platte-Arkansas River divide (Palmer divide) near Palmer Lake; its west fork heads in the mountains west of Larkspur, with some tributaries heading in the mountains farther north. Much of the gravel along Plum Creek has been derived from the Dawson Arkose, which is almost entirely reworked granitic material. Gravel derived from the mountains also consists of granitic material, inasmuch as the mountainous part of the drainage is underlain by Pikes Peak Granite. Gravel in the east fork drainage contains pebbles of Wall Mountain Tuff, a dense silicic volcanic rock that is likely to react deleteriously with high-alkali cement if used for concrete aggregate. Granule and pebble sizes compose about half the gravel along Plum Creek and sand about half. The gravel commonly is about 11 m thick but locally is as much as 18 m thick.

CHERRY CREEK

Cherry Creek heads at the Palmer divide east of Monument and flows north into the South Platte River in Denver. Its gravel is derived from the Dawson Arkose and the Castle Rock Conglomerate and consists mainly of granitic detritus and minor volcanic fractions. Mostly small granules and pebbles compose about 50 percent of the gravel. The gravel is 6–15 m thick.

MONUMENT CREEK AND FOUNTAIN CREEK

Fountain Creek flows southeast from the mountains west of Colorado Springs through the city. Monument Creek joins Fountain Creek from the north. The gravel along both streams consists mainly of granitic material derived from the Pikes Peak Granite and the Dawson Arkose. Granules and pebbles make up about 50 percent and sand, 25–40 percent, along both streams. The remainder of the gravel is fines and oversize stones. The valley of Monument Creek contains little gravel north of Colorado Springs. South from Colorado Springs the gravel is about 3–15 m thick and locally is as much as 25 m thick. It is thickest along the east side of Fountain Creek southeast of Colorado Springs.

UPLAND GRAVEL DEPOSITS ON PEDIMENTS AND HIGH-LEVEL TERTIARY SURFACES

Most of the gently sloping benches just east of the mountain front and many of the drainage divides in the eastern part of the area are mantled by Pleistocene gravel deposits that lie 25–30 m or more above stream level. In the mountains, scattered patches of older Tertiary gravel lie hundreds of meters above present day main-stream levels. Most of the upland gravel was deposited by Quaternary streams emerging from the mountains, shifting their courses from side to side and probably merging laterally. The deposits, therefore, reflect the character of the rocks in adjacent drainage areas of the mountains to the west. At Rocky Flats, east of Coal Creek Canyon, for example, the deposits contain as much as 80 percent quartzite, which was derived from Precambrian terrain in the mountains.

The amount of oversize material (cobbles and boulders) in the upland gravel is highly variable and is as much as 25 percent. Thus deposits at Rocky Flats and on benches adjacent to Bear Creek contain large amounts of oversize material, but deposits adjacent to the South Platte River or to Plum Creek contain little or none and, generally, more than 50 percent granules and pebbles. Thick soil profiles generally contain much clay and caliche (calcium carbonate). Long weathering has partly or completely disintegrated many stones, but the quality of the gravel can be improved by washing, crushing, and screening.

Generally, only small amounts of these deposits have been used locally for highway or road construction. An exception is the deposit on Table Mountain, 9.7 km west of Longmont, where the Boulder County Road Department has a large pit. This coarse deposit is as much as 5 m thick. About half the stones are granitic rocks, about 20 percent are red sandstone, 15 percent are gneiss, 10 percent are porphyry, and 5 percent are quartzite. About half the stones exceed 5 cm in diameter.

Some upland gravels are remnants of long, narrow stream deposits. An example is a discontinuous line of small deposits, including Riley Mound, on the drainage divide between the South Platte River and Beebe Draw. These deposits are mostly about 1.5 m thick, but some of them are as much as 4.5 m thick. They are deeply weathered and partly cemented by caliche. Pebble counts suggest that prolonged weathering altered many stones to clay and sand. The gravel is 50-65 percent quartzite, 25-35 percent granitic rocks, about 5 percent gneiss, 5-12 percent sandstone, and the remainder other rock types such as conglomerate and dark, fine-grained igneous or metamorphic rocks. Linear, discontinuous gravel deposits that trend southeastward from the foothills toward Longmont once filled ancient channels of the Little Thompson River.

A few patches of older gravel 3-6 m thick lie 100 m or so above stream level in the mountains along West Monument Creek. These deposits contain stones that are mainly Pikes Peak Granite. They generally contain more than 50 percent granules and pebbles and little oversize material, but chalky calcium carbonate is abundant, especially in the upper few feet. Considerable chemical decomposition degrades their quality, but despite their poor quality, they have been used extensively in the Colorado Springs area.

CONGLOMERATE

Conglomerate (cemented gravel) is a generally inferior source of gravel in the Front Range Urban Corridor. Three formations are potential sources, the Green Mountain Conglomerate west of Denver, the Castle Rock Conglomerate, and parts of the Dawson Arkose. The Green Mountain Conglomerate forms the upper part of Green Mountain. The lower 15 m of this deposit is a cobble-and-boulder conglomerate that contains pebbles of andesite, gneiss, pegmatite, quartzite, and sandstone (Scott, 1972a). Andesite decreases in abundance upward. The lower 15 m of conglomerate is overlain by 46 m of sandstone and conglomerate, overlain by 75 m of interbedded thin-bedded claystone, siltstone, sandstone, and conglomerate, overlain by about 60 m of conglomerate at the top.

Well-cemented Castle Rock Conglomerate underlies the divide between Plum Creek and Cherry Creek. This conglomerate is generally less than 15 m thick. Most of the pebbles are granite, gneiss, quartzite, and white vein quartz (Richardson, 1915). Chert pebbles and rhyolitic ash-flow tuff are less common. Although the deposit contains some boulders 30 cm or more in diameter, most stones are only slightly larger than 5 cm. The sandy matrix is cemented by silica, hence, most of the formation would have to be quarried and crushed for reduction to aggregate. Locally, however, the basal part of the formation is less well cemented and is scraped up for direct use on secondary roads.

Conglomerate is extensive in two areas of the Dawson Arkose. One is in the northwesternmost exposures of the formation in Douglas County, and the other extends from a point southeast of Parker to the El Paso County line. Granitic stones predominate; little material is oversize.

CLAYROCK

Clays and clay products have been produced in and near the Front Range Urban Corridor for more than 100 years. The major manufacturing centers are in Denver and Pueblo; brick kilns also operate near Longmont and Valmont in Boulder County. Pits and subsurface mines that supply these centers are within 80 km of Denver and Pueblo. Within a marketing radius of about 480 km, the two centers supply much of the Rocky Mountain region and parts of the adjacent plains with brick, tile, sewer pipe, and other clay products.

Refractory products made in the Pueblo area are blended from fire clay mined locally and Missouri fire clay or Arkansas bauxite. Porcelains for technical use, now manufactured in Golden in Jefferson County, combine out-of-State clays (kaolinite from Florida and North Carolina, ball clay from Tennessee and England) or use aluminum oxide in place of clay. These porcelains are distributed throughout the country. The fire clays of the Denver area, formerly used for refractory purposes such as lining metallurgical furnaces, are now blended with other, lower quality clays to increase structural strength and hardness of sewer pipe and some brick and tile (Patterson, 1964). Pottery clays are similar to fire clays in their high firing temperatures, but they require very low iron content (to avoid unwanted coloration) and high plasticity; they have been produced in both the Denver and Colorado Springs areas. Formerly they were used for the industrial porcelains made in Golden as well as for pottery. Most deposits of pottery clay in the urban corridor, however, are very small; consequently, with a few exceptions, art pottery and flower pots for commercial use are made of local brick clay that is blended with pottery clay from other States.

The clayrocks of the corridor vary greatly in character from one rock stratum to another and within each stratum. Some characteristics permit the manufacturing of an exceptionally wide range of finished clay products of differing structural properties and colors; others preclude commercial use. Clays from a dozen or more localities may be blended for one product, or one or two clays may suffice.

SOURCES AND PRODUCTION

Clayrock in the urban corridor is produced mainly in two areas: (1) in or a few miles east of the hogback belt from Boulder south to northwestern Douglas County; and (2) in northeastern Douglas County, in northwestern Elbert County (Kiowa-Bijou Creeks area), and near Calhan in El Paso County. The Kiowa-Bijou basin and Calhan areas are outside the urban corridor, but are within the source area for Denver manufacturers of brick, tile, and pipe. The productive strata in these areas are discussed in the following text. Clay mines and pits in these units were comprehensively reviewed by Van Sant (1959). The geology of clayrock in the Dakota Group in the central and northern part of the corridor has been discussed in detail by Waagé (1961).

Statistics on clayrock production by rock units or for specific areas of the urban corridor have not been published. An industry estimate of recent eastern Colorado production attributed a little less than one-half the production to the Laramie Formation, about one-third to clay lenses within the Dawson Arkose, and smaller amounts to the Dakota Group, the Benton Shale, the Arapahoe Formation, and the Pierre Shale. This assessment does not include Pierre Shale that has been mined for the production of lightweight aggregate in the Rocky Flats area in northern Jefferson County. The U.S. Bureau of Mines, however, includes production from the Pierre Shale for aggregate in its annual statistics on the output of clay and shale in Jefferson County. For 1971, the bureau reported 376,571 t valued at $763,000 from Jefferson County (probably in major part from the aggregate operation) and 13,509 t valued at $19,000 from Boulder County. Tonnage and value from Douglas, Elbert, and El Paso Counties were included with figures for three other counties outside the urban corridor for totals of 98,851 t and $214,000 (Kuklis, 1971).

DEVELOPMENT PROBLEMS AND PROSPECTS

As population and industry expand in eastern Colorado, the need for brick, tile, and pipe must be supplied from new as well as old workings. Clayrock exposed in outcrop or under shallow soil cover has been the chief source of past production. Future production will come from a small part of the areas of outcrop, and will be determined by interrelated factors of geology, economics, and competitive land use.

The maximum extent of an operation may be limited by the lateral limits of commercial quality or thickness of clay, by overburden too thick for stripping at prevailing clay prices, or by availability of mining rights. The minimum objective for major operators may be a deposit that can provide 9,000 t per year for 5 years and requires little or no selective mining. On this scale of operation, a deposit about 2–3 m thick in nearly flat lying rocks may require excavation of less than a hectare. Certain multiple-bed operations of 6–16 ha (hectares), as estimated in part from topographic maps, in the steeply tilted Laramie Formation north and south of Golden, have been active for periods longer than 5 years.

Overburden in strip-mining areas consists of gravel, sand, soil, or noncommercial bedrock. The thickness of unconsolidated surficial deposits may be as much as 20–25 m or more in alluvial valleys such as that of the South Platte River and Fountain Creek, and in a few upland areas between drainages. In much of the urban corridor east of the mountains, however, surficial sediments are less than 10 m thick and in many places are only 1–5 m thick (Hamilton and Owens, 1972a; Smith and others, 1964).

The amount of overburden that the mine operator can afford to remove varies directly with the thickness of the minable clay and inversely with hauling distance to the manufacturing plant. Recent allowable costs of less than $4.00 per metric ton for most structural clays when delivered to the plant site dictate that the ratio of overburden to clay thickness should not exceed 5:1 at a distance of 48 km or 3:1 at 100 km from the plant. These figures do not include the possible reduction of cost through marketing of sand or gravel from the overburden, or coal from the lower part of the Laramie Formation, and the cost of restoring the land surface after excavation of the clay is not included. (These statements are based on 1974 and earlier data.)

The most obvious restriction on areas of potential production of clay (and other nonmetallic mineral resources) is spreading urbanization. Front Range Urban Corridor base maps show urbanization plus lands set aside for military reservations, other government installations, recreation areas, flood-control reservoirs and reserves, and airports. Not shown are crop and grazing lands, which account for the largest nonurban use in the corridor east of the mountains, especially north of Denver (Driscoll, 1974a, b), urban fringe areas of predictable growth, and areas undeveloped but already zoned for residential and industrial use.

In addition to the above factors that affect clay production in the urban corridor, the location of the outcrop, history of development, and distinctive geologic character of the deposit also influence potential yield. Rocks of the Dakota Group and the Benton Shale (or its equivalents; the Graneros, Greenhorn, and Carlile) are accessible only in the narrow zone of the hogback belt, where the rocks are steeply tilted and locally faulted or folded; locally they are omitted at the outcrop by faulting. To date, mining of the Pierre Shale and Laramie and Arapahoe Formations has been almost entirely within the hogback belt, but these formations also are accessible to the east in the piedmont. The western margin of the Dawson extends to the mountain front locally between Denver and Colorado Springs, but the Dawson is exposed and mined in a much wider area south and east of Denver. Widespread exposure provides the possibility, but not the promise, of greater future production.

PRODUCTIVE ROCK UNITS

DAKOTA GROUP

The Dakota Group is the only major source of refractory clay in eastern Colorado. Intensive mining of Dakota clays in Douglas, Jefferson, and southern Boulder Counties from the 1860's to the present has substantially reduced the easily accessible supply of high-quality refractory clayrock. Remaining known reserves are mostly in properties currently in production or held by major producers. Additional clayrock of commercial quality exists in previously worked areas at depths below present economic limits of mining and in areas where mining rights are not available. Before 1909, Dakota clays mined in the Colorado Springs area supplied part of the material required for local brick factories; thereafter, the growing city obtained its clay products mainly from Denver or Pueblo. Limited production of pottery clay continued in the Colorado Springs area (Argall, 1949).

The strongly refractory quality of much of the Dakota Group clay in the Greater Denver area, as well as in the Pueblo area, is attributed to a very high content of the clay mineral kaolinite. North of Coal Creek, northwest of Denver, kaolinite decreases markedly and illite is the dominant clay mineral (Waagé, 1961, p. 20–23). Very little clay has been taken from the Dakota in this northern area. Nonrefractory clay from the illitic part of the Dakota would have to compete with similar clays from other deposits closer to Denver. Also, Dakota clays are less well exposed in the northern part of the corridor than in the central and southern parts and, therefore, both their quality and quantity are more difficult to evaluate.

BENTON SHALE

The basal part of the Benton Shale (equivalent to Graneros Shale), directly above the uppermost sandstone of the Dakota Group, is mined and blended with other brick clays. It is produced both north and south of Golden in conjunction with clay of the Dakota or is mined independently. Small amounts of pottery clay occur at the base of the Benton (Vanderwilt and others, 1947, p. 239–240), but the higher parts of the formation are not used in the manufacturing of clay products because they contain large amounts of limy shale, limestone, and siltstone.

PIERRE SHALE

The Pierre Shale is the thickest clay-producing rock in the corridor, ranging from about 900 m in part of the Colorado Springs area to 2,000–2,500 m in the northern counties. Although much of the Pierre is sandstone and siltstone, and the clayrocks now make only a minor contribution to the brick industry, the formation is widely accessible in the northern and southern parts of the corridor and has attracted the interest of brick manufacturers in a time of anticipated shortage and high cost of fuel. Improvements in technology now under investigation may allow use of the Pierre in making brick at relatively low firing temperatures. If successful, brick from Pierre Shale can be substituted in part for present higher temperature products that require more fuel. Early brick plants in the Colorado Springs area used local Pierre Shale, but they have been inactive for many years. Use of the Pierre for expanded lightweight aggregate is discussed in the section on "Expandable shale."

LARAMIE FORMATION

The Laramie Formation is much thinner than the Pierre, averaging about 75 m in thickness near Colorado Springs and 180–215 m near Denver; it has been described in various localities as containing 26–40 clayrock subunits, interbedded with sandstone, siltstone, and, in the lower part, subbituminous coal. Most or all of the clayrock units have been mined in one or several localities, and some of the most extensively worked units, in the lower part of the formation, contain clay of low-grade refractory quality. Sandstone in the lower part of the Laramie is a source of sand added to the clay to control shrinkage in firing and can be mined in some places with the clays in a single-pit operation. At present the Laramie provides more structural clay than any of the other clay-bearing units in the urban corridor and may be the largest source for the foreseeable future.

ARAPAHOE FORMATION

The Arapahoe Formation crops out in a narrow belt west of Denver and in a wider area northwest of the city. The formation is 75–120 m thick and contains silty claystone in some places, although much of it is sandy or locally conglomeratic and is not suitable for clay products. Within its limited area of outcrop, the formation has produced small amounts of structural clay. One clay pit east of Morrison is in the Arapahoe, and a recent development has been reported north of Golden.

DAWSON ARKOSE

The Dawson Arkose was deposited contemporaneously with and subsequent to the Arapahoe Formation and the overlying Denver Formation. These formations were deposited by laterally shifting streams issuing from the Front Range. The deposits differ in composition and texture depending on the mountain source rocks from which they were derived. The Dawson Arkose was deposited along ancient streams that drained Pikes Peak Granite terrane west of the Castle Rock-Colorado Springs area (Richardson, 1915; Waagé, 1952). The arkosic (feldspar-bearing) conglomerate, sandstone, and subordinate amounts of finer grained sediments (including clay) are thickest—as much as 600 m—on parts of the divide between the South Platte and Arkansas Rivers. In much of the area of greatest thickness, however, only the uppermost few hundred feet crop out. Most of the clay pits are in this upper part of the Dawson on the north flank of the divide in the Louviers-Parker-Castle Rock triangle within the corridor and in the Kiowa-Bijou basin area east of the corridor. Toward the north and south limits of the Dawson, erosion has cut away the higher parts of the formation, and the remaining rocks have yielded little or no commercial clay except in the Calhan area (east of map limit) northeast of Colorado Springs.

In the clay-producing units older than the Dawson the clayrocks are variable in thickness and lateral continuity, but tend to persist at certain levels within the formations. The Dawson, in contrast, contains few laterally persistent beds or zones of either clay or other rock types. The clayrock seems to be distributed randomly within the coarser sand and gravel. Within a single deposit the Dawson clays may vary in color from gray through green, yellow, and red, and streaks and layers of sand, silt, or mica flakes are common (Waagé , 1952, p. 386). Little selective mining is attempted, and the unsorted products are sufficiently valuable in the making of brick and tile to justify hauling distances that exceed those for nearly all other clays mined in Colorado for Denver plants. An eastward increase in fine sediments in the Dawson suggests that additional clay resources may exist near or beyond the eastern edge of the urban corridor.

The clay deposits near Calhan are south of the South Platte-Arkansas divide, about 65 km northeast of Colorado Springs (Richardson, 1911; Van Sant, 1959, p. 63). The clay-bearing zone is in lakebeds near the base of the Dawson. It is about 30 m thick and extends 4.8–6.4 km along the outcrop below surficial gravels of Quaternary age. Thicknesses of clay that can be extracted without selective mining of high-grade material range from 1–3.5 m. Like the smaller stream-laid deposits to the north, the clays near Calhan show wide variation in color, texture, and quality. Selected samples have low-grade nonrefractory to high-grade refractory ratings. For a number of years after initial production in 1903, the clay was sent to Pueblo for furnace linings, firebrick for buildings, and sewer pipe. More recently it has been used in the Denver area for structural clay products; its usefulness in mixture with other clays apparently justifies the unusually long hauling distance. Unworked high-grade refractory clay bodies are said to be in the area, but presumably they will not be developed while Dakota clays of comparable quality are available closer to the Pueblo manufacturing center. No other lakebed clays have been reported from the Dawson Arkose.

EXPANDABLE SHALE

As a resource category, expandable shale for use as lightweight aggregate for structural and thermal- or acoustical-insulation products is closely allied to clayrock. Expandable shale is obtainable from some of the same rock units and is similarly dependent on a high content of clay minerals (hydrous aluminum silicates). Expandable shale differs from clayrock in its physical properties and minor constituents, in the nature of its processing, and in the final products toward which processing is directed.

Although several rock types are suitable for making lightweight aggregates—including claystone; shale; slate; volcanic rocks such as scoria, cinder, pumice, and perlite; diatomite; and vermiculite—only expandable shale and claystone are abundant in the Front Range Urban Corridor. The Pierre Shale has been used recently in the urban corridor, and the Benton Shale and Arapahoe Formation are potential sources.

Processing involves crushing the shale and rapid kiln heating to 980°–1,200°C. In this temperature range the rock becomes viscous and finely porous (frothy) by the expansion of gases (CO_2, SO_2, H_2O) formed within the rock. The cohesive cellular finished product has a volume two or three times that of the original material: a density of 480-960 kg/m^3 (kilograms per cubic meter), in contrast to 2,400-2,700 kg/m^3 for sand and gravel aggregate. Furthermore, the expanded material has good structural strength and valuable thermal- and acoustical-insulating properties (Bush, 1964, 1973). One shale-expansion plant supplied by an adjacent quarry in the upper part of the Pierre Shale, though not presently active, operated for about 15 years in the Rocky Flats area between Golden and Boulder. It has a reported capacity of several hundred thousand metric tons per year and probably can supply requirements within a 320 km radius for the foreseeable future.

The suitablity of shale for commercial production of expanded lightweight aggregate cannot be evaluated in the field because many small differences in physical and chemical properties that may be critical in thermal processing must be kiln tested. In general terms, the most favorable rocks seem to be shales that are dark (gray, black, green), not extremely thinly laminated, and largely composed of illite and montmorillonite—the minerals dominant in clay-bearing rocks used for structural rather than highly refractory clay products. High concentrations of iron, alkalies, organic carbon, carbonate minerals, and silt may adversely affect the processing of the shale, but some of these components, finely and uniformly disseminated, are essential for the formation of the expansive gasses (Bush, 1973).

Because of its great thickness, the Pierre Shale could provide adequate resources of expandable shale for many years. It is 915-1,525 m thick in the Colorado Springs area and 2,135-2,440 m in the northern part of the urban corridor, and it is widely exposed.

GYPSUM

Gypsum (hydrous calcium sulfate, $CaSO_4{\cdot}2H_2O$) has been mined in the northern part of the Front Range Urban Corridor since the early years of this century for use as cement retardant, plaster of paris, plasterboard, other construction products, and as an agricultural soil conditioner Output has always been slight in comparison with that of several other nonmetallic minerals, and increased production seems improbable. Most of the deposits are small or of nonuniform quality, and adequate supplies of gypsum are readily available from other sources in and out of Colorado.

The Lykins Formation in the hogback belt near the mountain front contains most of the gypsum in the northern part of the corridor. The Ralston Creek Formation, adjacent to the Lykins on the east, contains subeconomic deposits south of Morrison in Jefferson County, in the Perry Park area of Douglas County, and in and south of the Colorado Springs area in El Paso County.

In Larimer County, gray to white, massive, finely crystalline gypsum in the lower part of the Lykins forms lenticular beds 0.3-15 m thick and mostly a few hundred meters long. Beds rarely are as long as 1.5 km. Gypsum of minable grade in many places is interbedded with and grades laterally into impure red gypsum and shale (Withington, 1964, p. 193). A small amount of anhydrite (nonhydrated calcium sulfate) is associated with the gypsum in this area. Anhydrite is considered a contaminant in gypsum used for plaster products, but it is not detrimental in small amounts with gypsum used as a cement retardant or as a soil conditioner (Williamson, 1963, p. 3, 9; U.S. Bureau of Mines, 1965, p. 416).

The only gypsum deposits now worked in the urban corridor are on the flanks of a partly eroded fold in the Lykins Formation about 8 km west of Loveland. Production has been nearly continuous since 1896. These deposits formerly supplied a local plaster mill; more recently they have provided gypsum used as a setting retardant in cement. A lenticular mass about 12 m thick and sloping at a low angle has been quarried for about 0.8 km along the east limb of the fold; a shorter west-limb pit is in two other beds of gypsum, each about 7.5 m thick, and dipping about 45°. All three beds pinch out at shallow depths. Similar gypsum deposits flank folds in the lower part of the Lykins north of the mapped area, two of which have produced gypsum in recent years (Story and Howell, 1963, p. 258-260; Colorado Division of Mines, 1973). In areas south of Loveland, the Lykins is reported to contain little or no gypsum.

Near Perry Park, southwest of Castle Rock, gypsum was quarried in the Ralston Creek Formation from 1898 to 1901 (Argall, 1949, p. 228). West of Colorado Springs, gypsum beds 6-18 m thick and partly of good quality (although interbedded with claystone), occur in the Ralston Creek Formation at Glen Eyrie, in the Garden of the Gods near Fountain Creek, and locally farther south. Until 1907, the Fountain Creek deposit intermittently supplied gypsum for a plaster mill near Colorado City (Withington, 1964, p. 193).

IGNEOUS AND METAMORPHIC ROCKS

Igneous and metamorphic rocks of the urban corridor have supplied small amounts of nonmetallic materials for various uses over the past century including: crushed or broken rock (concrete aggregate, riprap, road metal, roofing granules, precast construction panels, and other uses); dimension stone (building stone, paving blocks, monuments); landscaping rock; and minerals for chemical and metallurgical uses. The role of these rocks in the economy of the area may grow larger as more crushed rock is needed to supplement declining supplies of gravel. Igneous and metamorphic rocks have been mapped and described in conjunction with reviews of gravel resources of the urban corridor by Trimble and Fitch (1974a, b), Colton and Fitch (1974), and Schwochow, Shroba, and Wicklein (1974); the following statement was summarized from these publications.

IGNEOUS ROCK

The igneous rocks east of the Front Range are dominantly fine grained; those within the Front Range are dominantly coarse. Each group, however, includes a range of textures and compositions that affect commercial use. East of the mountain front, near Golden, three dark, fine-grained lava flows (Table Mountain Shoshonite or mafic latite) in the upper parts of North and South Table Mountains were first used as high-quality cobblestone and as building stone, also of good quality, but not popular because of its dark color. In recent years this rock has been quarried for tough and durable riprap and crushed for road metal and nonreactive concrete aggregate. Chemically and physically similar but somewhat coarser grained rock has been quarried from a dike near Valmont northeast of Boulder and from the Ralston dike northwest of Golden. Another crushed-rock quarry operates in a rhyodacite sill about 3 km southwest of Lyons. Other small bodies of igneous rock in the Golden-Boulder-Lyons area may be suitable for similar use. Light-colored rhyolitic Wall Mountain Tuff caps small buttes and underlies broader areas on mesas near Castle Rock and south to the Douglas County-El Paso County line. The Wall Mountain Tuff has provided building stone for homes and small office buildings in Denver, Colorado Springs, and Pueblo and has been used for road metal. It contains material that may be reactive with common cement and would be suitable for concrete aggregate only in low-alkali cement.

Coarse-grained plutonic igneous rocks, whose outcrops occupy nearly two-thirds of the east slope of the Front Range within the corridor, are now of economic interest chiefly as sources for nonreactive aggregate and other crushed-rock uses. Until the early 1930's, these rocks were quarried in a few places for building and monument stone; limited quarrying of monument stone has continued in the northern part of the area. In many places the coarse-grained igneous rocks are disintegrated by weathering to depths of about 4–10 m and are used locally for surfacing mountain roads (Scott, 1963). Unweathered igneous rock is available for crushing from three widespread rock formations and from others more locally. The three major units are Boulder Creek Granodiorite extending north from the Coal Creek area; Silver Plume Quartz Monzonite, mainly west and southwest of Denver; and a nearly continuous mass of Pikes Peak Granite between the South Platte River and Little Fountain Creek. The Silver Plume is rated highest for unweathered crushed-rock aggregate because tightly interlocking mineral grains resist abrasion and facilitate crushing to controlled size. The tendency of the Pikes Peak to separate along grain contacts may cause excessive breaking during crushing but results in effective natural disintegration. The Boulder Creek is intermediate in rating. Suitability for crushing may vary in different areas of each formation. Quarrying of unweathered rock requires blasting.

METAMORPHIC ROCK

Metamorphic rocks underlie a third or more of the Front Range area along the west margin of the urban corridor. These rocks are mostly coarsely layered to finely laminated gneiss and schist and, in the Coal Creek area, well-bedded, hard quartzite. For crushing, gneiss is generally better than schist. The Coal Creek Quartzite is a potential source of high-quality crushed rock. Quarrying any of these rocks requires blasting. Recent production of crushed metamorphic rock has depended in part on accessibility and closeness to the Greater Denver area market. In the foothills west of Denver gneiss is quarried for riprap and aggregate.

VEIN ROCKS

Tabular bodies of vein or dike rocks, cut the crystalline core of the Front Range within and west of the urban corridor. Usually coarse grained, these rocks have furnished small amounts of feldspar, mica, quartz, and fluorite for industrial use. In general, the Front Range deposits are not now economically competitive with sources outside the State.

LIMESTONE

Limestone is quarried in the Front Range Urban Corridor mostly for crushed rock and portland cement. In the past 100 years or more, the limestone has also been quarried for mortar, agricultural lime, poultry grits, sugar refining, metallurgical processes, and other industrial and municipal uses.

Many industrial applications require conversion of high-purity limestone, containing as much as 95–97 percent calcium carbonate, to quicklime (anhydrous calcium oxide, CaO) or slaked lime (the hydrous oxide, $Ca(OH)_2$). Conversion may be an integral part of the manufacturing process, as in sugar refining, or the user may buy commercially prepared lime. Sources outside the urban corridor in Colorado, Missouri, South Dakota, and Utah supply much of the local need for very high calcium limestone and prepared lime. Economically accessible supplies in the corridor area are no longer adequate. Some byproducts from recent sugar refining and from old lime ponds at refineries in the corridor have found a market as soil stabilizers along newly constructed roads and runways and in treatment of water supplies, sewage, and mine and mill waste.

Limestone resources of the urban corridor are accessible in or near the hogback belt and in a westward extension of sedimentary rocks in the Front Range near Colorado Springs. Of the several rock units within the area that contain limestone, only the Paleozoic formations in the southern third of the corridor, and the more extensive Cretaceous Niobrara Formation have had sustained economic importance. The Glennon Limestone Member (LeRoy, 1946) of the Lykins Formation has been quarried to a limited extent. Like records of other resources of low unit value and intermittent extraction, the records of limestone production in the corridor are incomplete.

MANITOU LIMESTONE AND ASSOCIATED ROCKS

In the southern part of the urban corridor, the westernmost and oldest source of limestone is the Manitou Springs area west and northwest of Colorado Springs (Scott and Wobus, 1973). Smaller outcrops extend along the mountain front north to Perry Park and south beyond the area. The productive formations are the Manitou Limestone (the major source of limestone but probably absent at Perry Park) and Williams Canyon and Leadville Limestones in the Manitou Springs area and locally north to Perry Park. The Manitou is about 56 m thick near Manitou Springs, 85 m near the Air Force Academy, and less than 30 m in several other outcrop areas. In the Manitou Springs area, the Manitou Limestone is underlain by 4.5–12 m of Peerless Dolomite and overlain by about 40 m of Williams Canyon and Leadville Limestones. These other limestone and dolomite units are quarried with the Manitou near Colorado Springs.

The carbonate rocks of this area are not uniform in composition or, consequently, in utility and value. In the two large quarries at the mountain front northwest of Colorado Springs and in some of the smaller quarries in the Manitou Springs area, quarrymen in past years have separated beds of almost pure calcium carbonate, as much as 3–3.7 m thick, from softer dolomitic (high-magnesium) beds and hard, impure, siliceous limestone. Color differences afford a basis for separation. Until the early 1940's, the high-calcium layers provided lime for sugar refining, which requires 97 percent or more calcium carbonate and strength to withstand the weight of 15–25 m of crushed rock in vertical kilns. Limestone from the Colorado Springs-Manitou Springs area supplemented production from the Ingleside Formation, north of the urban corridor. The Ingleside has been the principal in-State source of limestone for eastern Colorado sugar refiners since the turn of the century (Berlin, 1964, p. 203). (The Ingleside extends into the northern part of the corridor but contains no commercial limestone there.) The high-purity limestones of the Manitou Limestone also were a source of prepared lime for the general market at least until 1968. Most recently, lime processed in the Colorado Springs area was marketed for use in soil stabilization and treatment of sewage and industrial wastes.

Since about 1950, two large mountain-front quarries northwest of Colorado Springs have produced crushed rock for concrete aggregate, road metal, hot-mix paving, gravel, riprap for dams, and miscellaneous construction-industry uses. These uses require breakage into clean, hard, roughly equi-dimensional pieces that can withstand heavy loads and a minimum of the costly selectivity needed in quarrying high-purity, color-free limestone for many chemical uses. Some of the limestone, however, has a high content of chert, which is deleterious in concrete aggregate because of a possible reaction between the chert and cement. Such a reaction weakens the finished product. Also, some of the carbonate rock is not durable enough for use as high-quality crushed rock.

LYKINS FORMATION

The Lykins Formation is mostly easily eroded sandstone and sandy shale, less than 61 m to more than 183 m thick, in a narrow zone in the western part of the hogback belt, between the more-resistant ridge-forming rock units. The Glennon Limestone Member (LeRoy, 1946) of the Lykins Formation is a hard, impure limestone layer 2.4–9 m thick in the lower part of the formation. The Glennon is characterized by wavy or "crinkled" bedding and an orange-pink to reddish-brown color that have made it attractive for use as decorative dimension stone. It has also been crushed for driveway surfacing. In earlier years the Glennon was burned for local use as agricultural lime and mortar, but because of its high content of silt, sand, chert, and iron, it is no longer competitive. The Lykins is currently less important as a source of limestone than as the only presently productive source of gypsum in the urban corridor.

NIOBRARA FORMATION

Limestone and limy shale from the Niobrara Formation have been used since 1899 by a cement plant near Portland, 32 km west of Pueblo, and since 1927 by a plant near Laporte, 6.4 km northwest of Fort Collins. Cement production began in 1970 at a plant and quarry a few kilometers southeast of Lyons on the Niobrara outcrop belt. Another quarry about 8 km northeast of Lyons was opened in 1974 to supply the plant southeast of Lyons. Past production from the Niobrara has come from many pits and small quarries along the length of the urban corridor, where the rock was burned locally for agricultural lime or for mortar. The basal limestone of the Niobrara has been quarried in a Douglas County locality for use in several of the more than 40 small foundries that have been operated in the Denver area (Scott, 1963b, p. 115; Carter, 1964, p. 204).

As exposed in the eastern part of the hogback belt, the Niobrara Formation consists of a lower (western) member called the Fort Hays Limestone and an upper, thicker member called the Smoky Hill Shale. The Fort Hays contains 5.5–12 m of limestone in beds as much as 0.6 m thick and in places exceeding 90 percent calcium carbonate; very thin interbeds of limy shale separate the limestone beds. The Smoky Hill consists of limy shale and impure, commonly chalky limestone, more than 150 m thick south of Colorado Springs, and about 90 m thick near the north end of the urban corridor. The northward thinning is not uniform.

Where the Niobrara is quarried for making cement, the Fort Hays averages about 85 percent calcium carbonate and the lower part of the Smoky Hill averages 50–65 percent. The two are blended to attain the 75–78 percent calcium carbonate content required for portland cement (Wolfe, 1964, p. 182). Shale in the Smoky Hill supplies the necessary alumina and part of the silica for the cement; additional silica is added from crushed sandstone from the Dakota Group. The upper part of the Smoky Hill contains pyrite and other impurities that preclude its use for cement. In some places in the northern part of the mapped area, the Smoky Hill contains enough kerogen (solid hydrocarbons that yield oil when undergoing destructive distillation) to approximate a low-grade oil shale. Efforts to remove the kerogen to reduce air pollution from the cement plant add to the technical problems of cement production.

Economic factors have restricted quarrying for cement to broad outcrops of flat to moderately tilted beds (less than about 25°) and thin overburden. These conditions exist for the Niobrara within the corridor (1) on parts of an en echelon fold from the Lyons area northward and (2) in the extreme southern part of the mapped area, in and adjacent to the Fort Carson Military Reservation. In the northern area, the steeper flanks of the folds dip 30°–70° or more.

Large-scale use of limestone from the Niobrara of the urban corridor for industrial processes or products other than cement seems unlikely in the foreseeable future. Commercial quantities of rock containing the 97 percent or more calcium carbonate needed for sugar refining and production of open-market lime, or the 95 percent or more needed for most metallurgical processes, are not generally present. Some additional rock of metallurgical quality may be available in Douglas County. Presumably, if local demand existed, lime or powdered limestone of about 80 percent calcium carbonate could be obtained for agricultural use from the Fort Hays wherever that member is also chemically suitable for cement.

SANDSTONE AND CONGLOMERATE

Sandstone from 10 or more rock units in the Front Range Urban Corridor has met widely varying needs for dimension stone, crushed rock, riprap, landscaping rock, silica rock, and sand in the past century. Quarrying operations, however, have been small at many locations, commonly intermittent, and often short lived. Records are incomplete.

Dimension stone, for supporting walls and foundations of buildings, was probably the principal use of sandstone until the early 20th century, when steel and reinforced concrete largely replaced stone for weight-bearing parts of large structures. Builders stopped using some sandstones such as the Fountain Formation and the Fox Hills Sandstone because these rocks lacked the strength and resistance to weathering available from more durable sandstones from parts of the Dakota Group and the Lyons Sandstone. Hard, conglomeratic sandstone in the Dawson Arkose in the Castle Rock-Colorado Springs area and Sawatch Sandstone in Ute Pass west of Colorado Springs also have been quarried for structural use. The Ute Pass locality provided a strong and durable, reddish, green-mottled sandstone in slabs as much as 30 cm thick and a few meters long. Later use of sandstone in buildings has been confined mostly to exterior facing and interior decorative applications; slab and crushed sandstone are also used for walks, patio paving, and landscaping (Lindvall, 1964; Sharps, 1963). Crushed or broken stone for road fill or riprap in dam construction is quarried locally.

As a source of silica sand for special industrial purposes such as glass making, urban corridor sandstones are only locally pure enough (high in silica and free from contaminants such as iron) and soft enough (weakly cemented). Sand prepared from local sandstone is presently used mainly in making brick, tile, and cement.

The following sandstones have been used in recent years:

LYONS SANDSTONE

The Lyons Sandstone crops out near the western edge of the hogback belt. It ranges from 215–245 m in thickness near Colorado Springs to less than 30 m near the north end of the area. It is suitable for either dimension stone or crushed rock where it is red to pink, uniformly fine to medium grained and nonconglomeratic, well cemented, thinly and flatly bedded, and splits easily into large slabs of uniform thickness. It is less used, either crushed or in slabs where it is gray to white or yellow, variable in grain size, poorly cemented, or thickly crossbedded. Light-colored, weakly cemented Lyons has been a local source of silica sand. Mudstone and siltstone interbedded with the sandstone in the Greater Denver Area reduce its commercial potential.

In the past, the Lyons Sandstone was quarried for dimension stone in the Colorado Springs area as well as in the northern part of the corridor. In later years, nearly all production—for facing of buildings, flagstone, crushed stone, riprap, and other minor uses—has come from quarries near Lyons and farther north. Many quarries have been opened but few if any have operated on a full-time basis or for long periods. Only about four to eight quarries are active in any one year. Moderate but persistent output can be expected to continue for many years.

Although the Lyons Sandstone in the central part of the hogback belt is generally inferior to that in the north and south for most uses, the local softness and very light color were turned to advantage early in this century when sand for colored glass bottles and furnace bottoms was obtained from a bed in the upper part of the formation near Kassler in northwestern Douglas County. The amount of high-purity soft stone, however, is too limited to encourage further development of glass-sand production.

DAKOTA GROUP

Sandstone from the upper part of the Dakota Group (South Platte Formation) provided dimension stone for many of the older buildings in eastern Colorado because of its hardness, strength, bedding that facilitated cutting of large slabs, resistance to weathering, and gray to light-brown color. Quarries operated southwest of Colorado Springs and in the Greater Denver area in the late 19th century. More recently, soft, white sandstone in the upper part of the Dakota both north and south of Kassler has been used as molding and core sand by foundries in the Denver area; iron-stained layers have been removed before crushing (Scott, 1963, p. 115). Since the 1970 opening of a cement plant southeast of Lyons, nearby outcrops of Dakota have supplied sand to control silica content of the cement. The Dakota has also been used as riprap in dams and as landscaping rock. Less sandstone is now quarried from the Dakota than from the Lyons.

SITE REHABILITATION

Nearly all urban industrial mineral extraction in the Front Range Urban Corridor leads to the excavation of open pits. A minor exception has been the underground mining of clay from certain hillside galleries in the Dakota hogback north of Golden where the clay has been block-caved and removed through adits. In any event, what happens to an excavation after mineral extraction stops has more long-term significance to the urban community than has the actual mining process. Past failure to rehabilitate excavations has led to visual blight and environmental degradation. For reasons of public safety, sanitation and health, visual amenity, and property value—in short, the quality of life in the vicinity of industrial mineral excavations— rehabilitation of exhausted pits is becoming a part of planned sequential land use. For example, gravel production may be followed by conversion of pits to lakes or by filling of pits for construction sites or park development. In recognition of this need, the Colorado Legislature in 1973 enacted into law a bonded reclamation plan.

Some worked-out pits in the Greater Denver area have been backfilled with urban refuse and reclaimed as valuable real estate. Major shopping centers and municipal facilities occupy some of the high-value reclaimed lands that contribute to the economic base of the community. Among these areas are Cherry Creek Shopping Center, the Denver Coliseum, and McNichols Arena-Mile High Stadium area. Other reclaimed lands have been converted to parks, such as Ruby Hill. To the extent that an exhausted pit can be rehabilitated for other use, the pit is an asset to the community rather than a liability.

The practice of backfilling excavations with urban waste is widespread in the Front Range Urban Corridor and undoubtedly will continue in the future. The potential for pollution, however, should be evaluated (fig. 17). Backfilling is a sound sequential land use provided that (1) pollution does not reach ground water, or

FIGURE 17.—Urban refuse backfilling an abandoned gravel pit near Clear Creek in Arvada. Waste-disposal practices as illustrated here, besides causing visual blight, attract vermin, generate gases, and contaminate the ground water. March 1976.

(2) pollution of shallow ground water is prevented by appropriate engineering design (McCollough and Pacey, 1971, p. 45), or (3) the leachates—aqueous chemical solutions—from the fill are acceptably diluted in the ground-water reservoir within acceptable distances of the land fill, or (4) the community is willing to accept pollution of the shallow ground water, as landfilling has been widely practiced in the area (Hansen, 1977, p. 45), or (5) due consideration is given the problems of gas (that is, methane) generation and subsidence.

The rate of natural dilution of leachate in ground water has not been monitored in detail in Greater Denver or in many other places in the United States for that matter (Schneider, 1970, p. F5). Schneider (p. F5, F6), however, has cited documented ground-water pollution in various places in Europe many meters distant from land fills and many years subsequent to dumping. The leachates that undoubtedly are being generated at numerous land fills in the Front Range Urban Corridor probably travel through pervious gravels well beyond the disposal sites, in concentrations that limit potential use of the water (U.S. Public Health Service, 1962). And the leachates probably degrade the surface water as well as the ground water.

Microbial and chemical decomposition of waste material in landfills, besides producing leachate, generates a variety of gases that can escape the landfill. One of the more common reactions in an aerobic environment is the production of carbon dioxide from the breakdown of cellulose. The CO_2 in the presence of water produces carbonic acid, which reacts with many components of the landfill, in turn raises the hardness of the water, and increases the biochemical oxygen demand (Schneider, 1970, p. F4). Anaerobic decomposition of cellulose and other organic substances leads to the production of methane, which is odorless, and ammonia or hydrogen sulfide, or both. All these reaction products can make their way into the hydrologic regimen or escape to the atmosphere. To help identify off-site environmental problems related to landfills in the Greater Denver area, the Geological Survey has prepared a map identifying known landfills in that area (McBroome and Hansen, 1978).

Gas generation and subsidence commonly occur together. As the fill material decomposes, it loses volume and simultaneously generates gases. Carbon dioxide evolves at a declining rate as the available free oxygen is consumed. Conversely, methane production increases until the nutrient level declines to the point where gas output decreases. If a landfill contains appreciable sulfate, such as gypsum board, hydrogen sulfide might result from reactions with carbonic acid.

The gases move outward and upward from the landfill into the surrounding media in response to pressure gradients and available escapeways. They may vent to the atmosphere or may accumulate in basements, sewer trenches, or other openings. Methane is lighter than air; carbon dioxide is heavier. In concentrations of 5–15 percent, methane is explosive. Lateral migrations of as much as 340 m have been documented and, because of large-scale ground subsidence, buildings and other structures have been endangered or damaged (Russ Herman, Raymond Vail and Associates, oral and written communs., 1978).

GRAVEL AND SAND PITS

When gravel or sand extraction is widespread below the water table, the operation lowers the water table significantly and alters the hydraulic gradient between adjacent pits. Inasmuch as the hydraulic gradient is a sloping surface, and the pond surface is flat, the water table is lowered upgradient adjacent to the pond by an amount equal to the gradient times the length of the pond. For example, if the gradient is 10 m/km and the pond is 0.4 km long, the drawdown is 4 m. Gradients and ponds of this order are commonplace along creeks near the mountain front. At an operating pit the drawdown usually is greater, inasmuch as pumps commonly are needed to keep the water from rising into the working area.

When a pit is depleted and extraction stops, the water surface in the pit stabilizes at a level close to that of nearby surface drainage downgradient from the pit. Some pits are worked to within a few meters of drainage; commonly a narrow levee is left to preserve the drainage course. The water budget of a pit pond, therefore, can be rather complex, depending partly on the slope and direction of the hydraulic gradient, the permeability of the gravel, the regimen of the nearby stream, and the evaporation rate, which, in this area, ranges from about 97 to 117 cm per year (Meyers, 1962, pl. 3).

All the major streams along which most gravel is being extracted in the corridor area have histories of repeated intense flooding (Follansbee and Sawyer, 1948; Hansen and others, 1978, p. 43). The wisdom of sequential use by backfilling and reclamation on flood plains, therefore, is questionable unless such sites are reclaimed for conforming uses that will tolerate intermittent flooding. Such potential uses include parks, golf courses and athletic fields, open space, parking lots, and, where the topsoil has been saved, renewed agriculture (fig. 18). Although many comprehensive community plans incorporate this concept, resistance in the form of citizen opposition to restrictions on land use has been voiced in public hearings and in letters to newspapers.

A nonpolluting alternative to landfilling that has high potential value to the community is to preserve and landscape the ponds themselves, modifying their shore contours as needed to make them attractive and safe for water-oriented leisure-time use. Such potential use includes boating, swimming, warm-water fishing, and onshore picnicking. This alternative has been advocated for the valley of Clear Creek by the City of Wheat Ridge, the Professional Engineers of Colorado, and the Colorado Chapter, American Society of Landscape Architects ("Action plan for Clear Creek," undated leaflet). This alternative also is supported by the National Sand and Gravel Producers Assocation (Soule, 1974, p. 18; Bauer, 1965; Schellie, 1963). Similar plans have been proposed for other gravel-bearing areas such as the valley of Boulder Creek.

Normally, this alternative calls for public ownership, although private development has had some success. Water-filled gravel pits along St. Vrain Creek near Interstate Highway 25 have been stocked with warm-water fish and made into a state park administered by the Colorado Division of Wildlife. The subject of urban lakes and their value in real estate is outlined by Rickert and Spieker (1971), who pointed out that suitable development can greatly enhance the value of adjoining property (see also David, 1968). Because of the semiarid climate of the Front Range Urban Corridor, natural lakes are few in number, mostly small in size, and often inacessible to the public (Ficke and Danielson, 1973; Danielson, 1975). The scarcity of open water in this environment enhances its value. Artificial lakes along the Colorado Piedmont, therefore, are potential real community assets, just as the many attractive natural water bodies are in cities such as Seattle, Wash.; Greater Boston, Mass.; and Minneapolis-St. Paul, Minn.

CLAY PITS AND STONE QUARRIES

Reclamation of clay pits and stone quarries presents problems that are similar to those faced in the sequential use of gravel pits. Large hillside quarry scars, however, may not be amenable to restoration, certainly not in terms of anything resembling the landscape prior to quarrying, and treatment, if any, is a difficult problem in landscape architecture.

Pits and shallow quarries along the Front Range, on the other hand, offer a chance of nearly complete reclamation, and the concept of sequential use can be built into the utilization procedure. The pits and shallow quarries are prime locations for well-

FIGURE 18.—Overland Park (background) and Ruby Hill Park (foreground), Denver. Viewed toward the southeast. Foreground area is a former waste-disposal site. Old clay pits on Ruby Hill were backfilled with refuse, regraded, and landscaped. Overland Park, on the floodplain of the South Platte River, also contains landfills. Overland Park has been inundated repeatedly without serious flood damage. October 1975.

engineered sanitary landfills. The chief constraint on reuse, the potential of offsite water pollution, is minimal and readily manageable in this setting because (1) surface runoff is minimal, (2) lowering or penetration of the water table in such areas is unlikely, and (3) the permeability of the enclosing wall rocks is very much lower than that of a terrace gravel along a major drainage, for instance. Migration of pollutants from the disposal site, therefore, could be expected to be slow and minimal. Moreover, backfilling with solid waste fulfills a community need for waste disposal.

Sequential use of pits and quarries along the mountain front presents some problems. Optimum compaction of solid waste in a steepsided pit or quarry is difficult, especially near the walls, partly because of the high and variable compressibility of most waste material and partly because mechanical compactors cannot maneuver easily near the walls, especially in long, narrow excavations. Moreover, slow decomposition of cellulose-based wastes gradually reduces the volume of the fill, and subsidence is likely for a long period of time. Past performance in the Greater Denver area shows that subsidence is a potential problem for buildings or other rigid structures sited on backfilled pits or quarries. Some form of open space, thus, seems to be the preferred sequential use for reclaimed clay pits and stone quarries along the Front Range.

COAL

Coal underlies parts of all counties in the Front Range Urban Corridor and has been mined from most counties in the past (figs. 19 and 21). Little if any coal is being mined in the area now, but a resumption of mining seems likely in the future. A very large coal resource still remains even though more than 100 million metric tons has been extracted (Lowrie, 1966, p. 9). Considerable socioeconomic and environmental impacts have resulted from past mining and would result from mining in the future.

A good summary of past coal production in the Denver region, embracing all of the Front Range Urban Corridor and including both Cretaceous and Tertiary coal, is given by Landis (1959), together with reserve estimates and brief descriptions of the coal, field by field.

A more detailed description of a Tertiary zone containing thick lignite beds in the Denver Basin northeast, east, and southeast of Denver is given by Soister (1974). Soister (1965a, b, c; 1968a, b; 1972) also has published several reports on individual coal-bearing quadrangles.

SUBBITUMINOUS COAL

The greater part of past coal production in the Denver region has been from beds of subbituminous coal, ranks B and C, from the Laramie Formation of Late Cretaceous age (Landis, 1959, p. 159–166). Distribution of this coal is indicated in table 2. Subbituminous coals of ranks C to B range from 8,300 to 13,000 Btu (British thermal units). Coal of less than 8,300 Btu is classed as lignite (American Society for Testing Materials, 1939).

A general idea of the depth of subbituminous coal beneath much of the Denver Basin can be inferred from maps by Romero and Hampton (1972) that show the approximate configuration and depth of the Laramie-Fox Hills aquifer. The coal-bearing beds are in the stratigraphic interval that immediately overlies the aquifer. Most of this coal is too deep to be mined by surface methods, and much of it is deeper than 300 m. The shallowest coal is peripheral to the basin; the deepest is southeast of Castle Rock at a depth of about 830 m.

LIGNITE

A huge resource of lignite, much of it strippable, is in the Denver Formation (Upper Cretaceous and Paleocene) just east of Denver (Soister, 1974). The lignite is in the Paleocene part of the formation. Using drill data, Soister found lignite within 300 m of the ground surface under an area 121 km long and 56 km wide from a point just northeast of Denver in Adams County south-southeast to a point several kilometers south of Calhan in El Paso County. The lignite-bearing zone ranges in thickness from 100 m or so to as much as 150 m. Individual beds commonly range from less than a meter to as much as 8 m; the thickest known bed, east of Denver near Watkins, has a gross thickness of 16.6 m, including non-coal partings. In most places, this bed is less than 60 m below the surface. Soister has traced it for at least 29 km, and he estimated its volume weight at 1.1 billion metric tons. Soister further estimated that in beds at least 1.2 m thick within 300 m of the surface the lignite resource is about 18 billion metric tons. Soister (1974, p. 41) suggested that most of the lignite cannot be exploited economically by conventional mining methods (except perhaps the thick, strippable beds). He regarded in situ gasification as most promising because of the numerous noncoal partings. Liquifaction or reconstitution, or both, are possible alternative methods, especially if the non-coal partings (clay) could be utilized as a byproduct. Under the old methods of mining, perhaps half the lignite extracted was discarded.

SURFACE EFFECTS OF PAST UNDERGROUND MINING

Most mining in the Denver region has been from coal beds in the Laramie Formation at depths ranging from zero at the outcrop to as much as 150 m. At the shallower depths, considerable ground subsidence has followed extraction, and in some places the timing and extent of subsidence has been nearly unpredictable. Particularly in the Colorado Springs and Boulder-Weld fields, urban growth is encroaching on areas where underground coal mining has been followed by ground subsidence (Colorado Springs Planning Department, 1967; Colton and Lowrie, 1973; Hansen, 1976, p. 97–100).

Collapse into mined-out workings has reached to the surface of the ground in some places, and the resultant pseudokarst topography has disrupted surface installations such as buildings, ditches, and railroad tracks. Where the depth of mining was shallow—several meters or so—the room-and-pillar patterns of working can be discerned in the collapse pattern at the surface (fig. 20). In some places the effect on the ground has been very disruptive. At shallow depths, strip mining would have recovered much more coal and would have been more amenable to restoration of the disturbed ground. The extent, duration, and time of collapse are complex variables related to the thickness of the mined coal, methods of mining, character of the roof rock, depth of mining, and ground water conditions. In recent years the Colorado Geological Survey has researched the problem of potential collapse but has not yet found completely satisfactory solutions (Myers and others, 1975). Near Marshall, just south of Boulder, the problem of collapse has been complicated by mine fires that have been burning for many years.

At Colorado Springs, some land above mined-out coal workings has been built upon successfully by means of bridging techniques such as grade beams that straddle the workings (Colorado Springs Planning Department, 1967, p. 7). This technique requires specific knowledge of the distribution of mined voids versus remaining pillars. Most mined areas of the Boulder-Weld coal field are still overlain by range or farmlands (Colton and Lowrie, 1973) where the economic consequences of collapse have been minimal. But urbanization is spreading into these areas, and development is proceeding cautiously. Some building and rezoning permits have been withheld by county authorities pending detailed evaluation of specific sites.

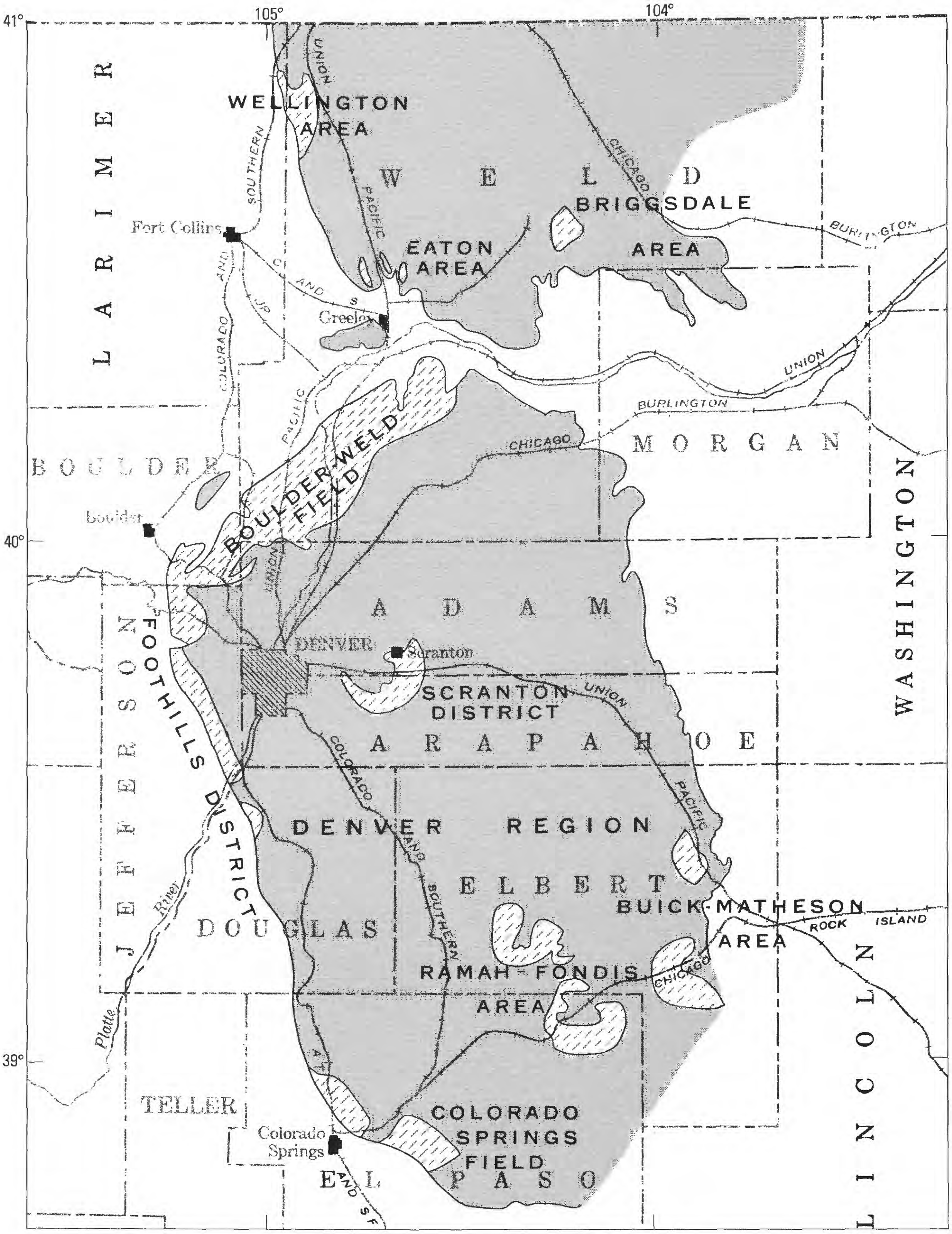


FIGURE 19.—Map showing distribution of coal (shaded areas) in the Denver Basin, Colorado, and location of fields from which coal has been produced (broken-line pattern). From Landis (1959).

TABLE 2.—*Summary of Cretaceous coal occurrences in the Laramie Formation, Denver region*
[Data from Landis, 1959, p. 159-166]

Field	Area (km^2)	Thickness of principal beds (m)	Estimated total before mining (million t)	Subbituminous rank
Colorado Springs.	176	4.3	367	C
Buick-Matheson.	205	No data	79	C
Briggsdale---	36	1.7	80	C
Eaton--------	23	.85	27	C
Wellington---	137	1.4-1.8	272	C
Foothills----	233	2.5-5.5	894	C to B
Boulder-Weld-	870	2.5-4.3	1,796	B

Unfortunately, studies are not always definitive. Mining began in the Denver region in the last half of the 19th century and some mines have been inoperative for more than 90 years (Colton and Lowrie, 1973). Particularly for very old mines, maps do not always adequately show the distribution of mined areas or the locations of haulageways, shafts, or winzes. Moreover, from the ground surface, it may not be possible to locate underground openings or determine the extent of collapsed workings at depth.

OIL AND GAS

The Denver Basin is one of the leading oil- and gas-producing areas of the Rocky Mountain States. In Colorado, only the Piceance Creek basin in the northwestern part of the State has produced more oil, and only the Piceance Creek basin and the San Juan Basin in southwestern Colorado and adjoining states have produced more gas. Estimates of ultimate gas production from the Denver Basin exceed that of either of the above basins (Haun and others, 1976, p. 6-8). Ultimate production estimated by Haun and others is 487,646,669 barrels of oil and 2,052,966,833,000 ft^3 (cubic feet) of gas. Through 1978, the Colorado part of the Denver Basin had produced 444.5 million barrels of oil and 962.7 trillion ft^3 of gas (Colorado Oil and Gas Conservation Commission, 1978, p. 8).[1]

Oil has been produced in the Denver Basin chiefly from areas east of the Front Range Urban Corridor, but Weld, Adams, Larimer, and Arapahoe Counties

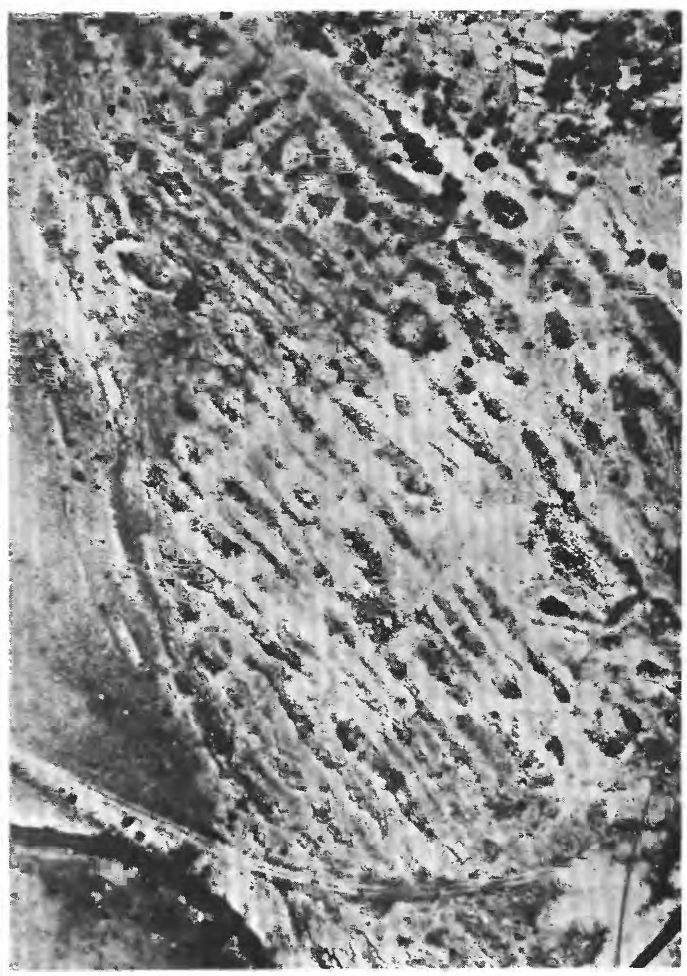
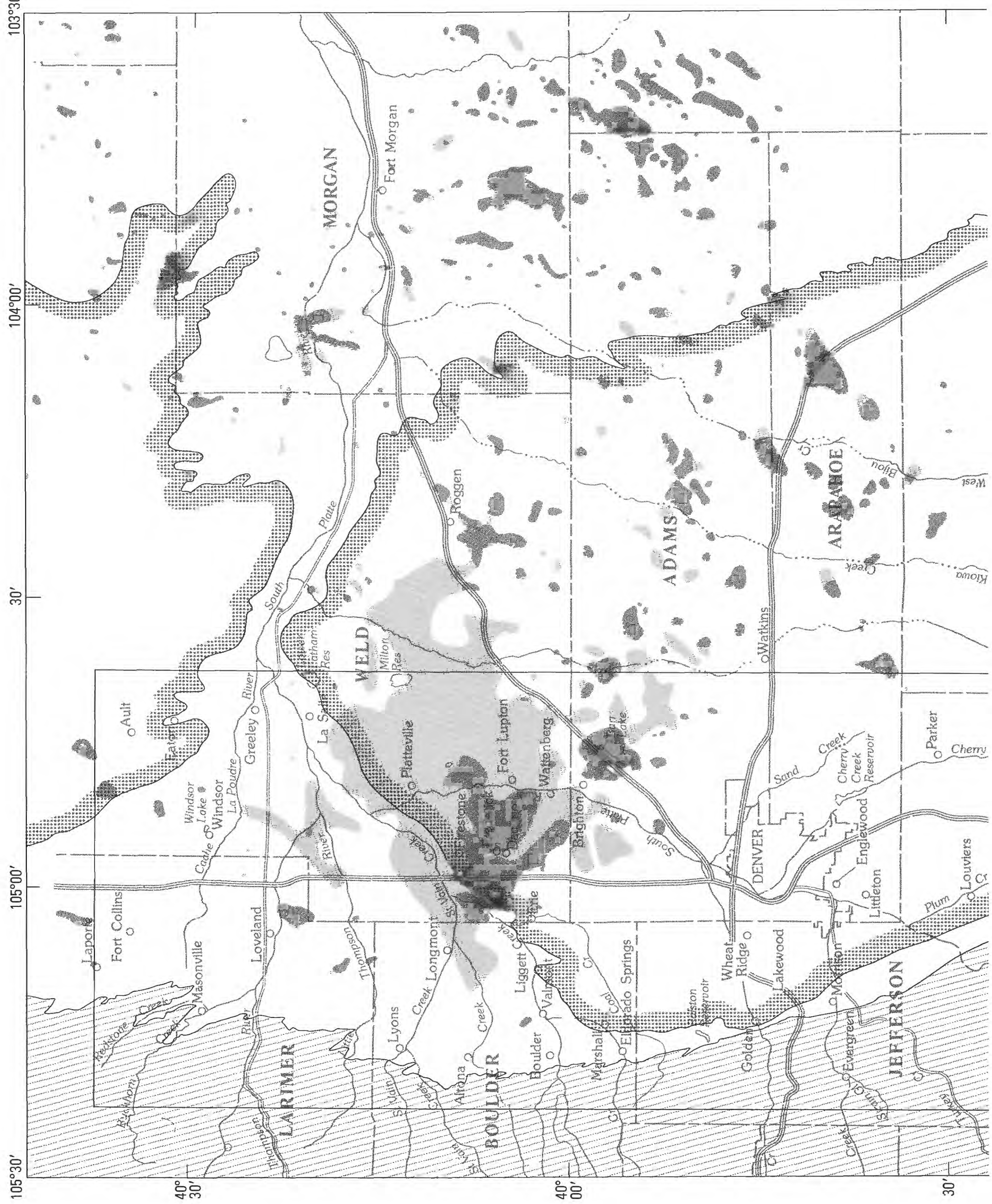


FIGURE 20.—Extreme ground subsidence over an old underground coal mine at Marshall, near Boulder. Room-and-pillar mining pattern is clearly indicated by collapse pattern of ground. Area shown is about 420 m long north to south; north is at top of photograph. Vertical aerial photograph by R. B. Taylor and R. L. Parker, U.S. Geological Survey, June 1973.

[1] The petroleum industry records its production figures in the inch-pound system of units. One barrel equals 0.159 m^3. One cubic foot equals 0.02832 m^3.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Fort Morgan
Roggen
Watkins
Parker
Englewood
Littleton
Louviers
Lakewood
Wheat Ridge
Golden
Morrison
Evergreen
Brighton
Wattenberg
Fort Lupton
Platteville
Firestone
Greeley
Eaton
Ault
Windsor
Windsor Lake
Fort Collins
Laporte
Masonville
Loveland
Longmont
Lyons
Boulder
Valmont
Liggett
Eldorado Springs
Marshall
Altona
Milton Res
South Platte River
Cache La Poudre River
Big Thompson River
Sand Creek
Cherry Creek
Cherry Creek Reservoir
Plum Creek
Kiowa Creek
Bijou
West
Coal Cr
St. Vrain Creek
Boulder Creek

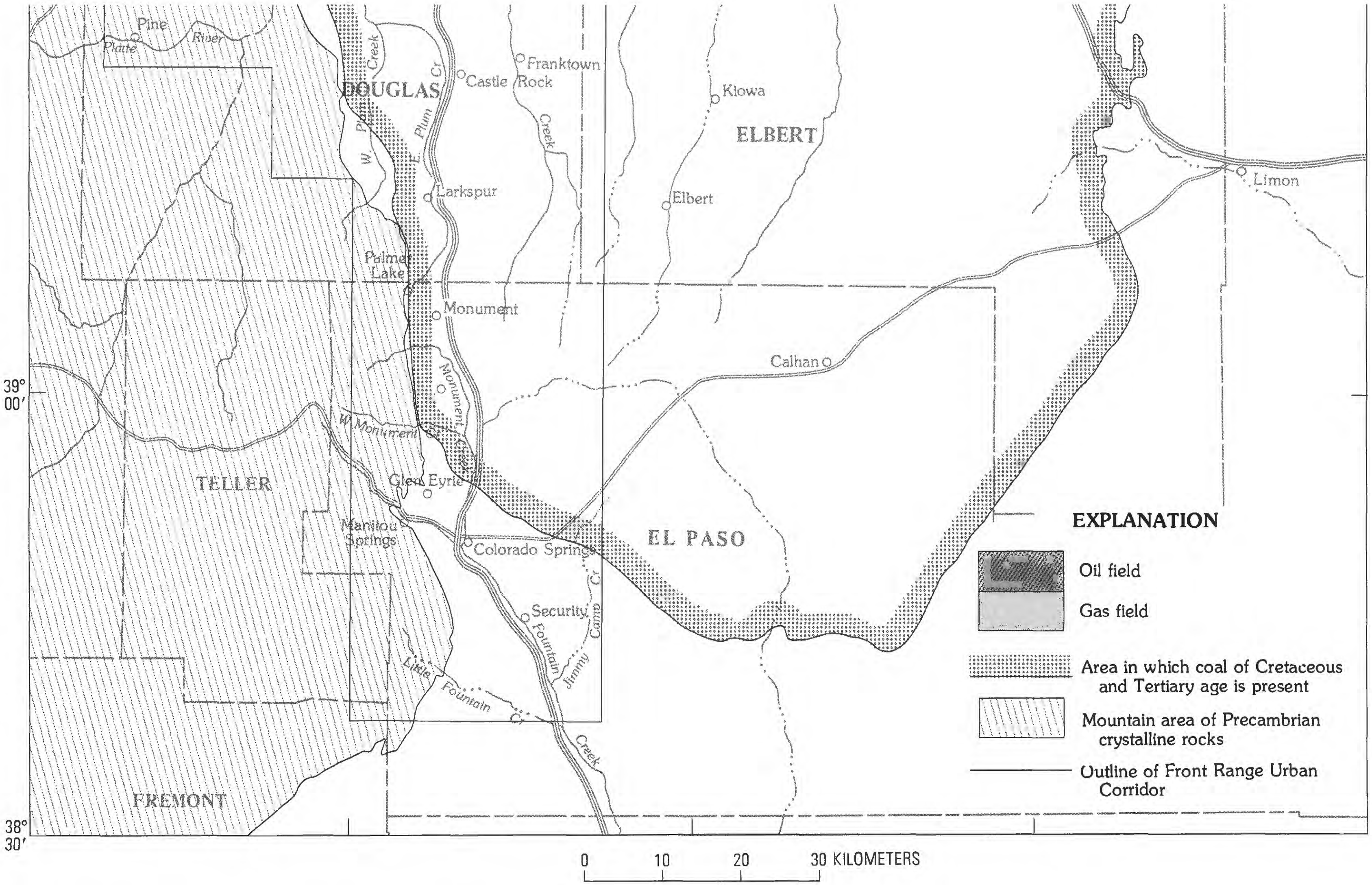

FIGURE 21.—Map showing distribution of oil and gas fields and coal in and near the Front Range Urban Corridor. Outline of corridor and mountain front (contact between Precambrian crystalline rocks on the west and younger sedimentary rock on the east) is also shown. From various sources in the U.S. Geological Survey and Colorado Geological Survey, and Tweto, 1976.

produce oil from many wells inside the corridor area, some close to dense urbanization (fig. 21). Boulder County has a long history of modest oil and gas production, and a little oil has been produced in Jefferson County.

By far the largest gas field in the Denver Basin is Wattenberg (named from the town in southwestern Weld County), which lies mostly in the Front Range Urban Corridor between Denver and Greeley. The Wattenberg field is one of the great gas fields of the Rocky Mountain region, and it has the highest estimated ultimate gas productivity in Colorado. Haun and others (1976) estimated that Wattenberg ultimately will produce 1,322,579,190,000 ft^3 of gas.

The scope of this report does not include a detailed account of production and potential development of oil and gas in the Front Range Urban Corridor; such a study was not a part of the urban-areas program of the U.S. Geological Survey. A voluminous literature has accumulated, however, particularly since the years immediately following World War II when exploration and development of oil and gas in the Denver Basin were greatly accelerated. Many papers consequently have been published on the stratigraphy, structure, petrography, paleontology, and depositional environments of the petroleum-bearing rocks and the fields in which they occur. Excellent papers have appeared in The Mountain Geologist, which is published by the Rocky Mountain Association of Geologists, in guidebooks of field conferences of various geological societies of the region, and in other technical journals (for example, Pruitt and Coffin, 1978).

The most productive reservoir rock in the Denver Basin is the "J" sandstone (economic usage). This sandstone is the uppermost member of the South Platte Formation of the Dakota Group in the Denver Basin and is the chief exploration target in most oil and gas fields of the basin. Petroleum geologists sometimes call it the Muddy Sandstone, a name more correctly applied to similar rocks in northern Wyoming. Production of oil and gas has also been obtained from many other stratigraphic intervals in the Denver Basin, especially from the Lyons Sandstone of Permian age, which is second only to the "J" sandstone in terms of total productivity, and from the Niobrara Formation and sandstone members of the Pierre Shale of Late Cretaceous age.

SOIL PROBLEMS

LAND DEVELOPMENT ON EXPANSIVE SOILS

Expansive soils cause construction problems on the Colorado Piedmont, particularly with respect to highways and lightly loaded structures such as private dwellings, schools and commercial buildings, and poured concrete slabs. Problems caused by expansive soil take the form of increased costs of preventive or precautionary construction and increased costs for repair of structural damage after construction—buckled and cracked pavements, cracked or heaved masonry walls, heaved floors, damaged structural members, jammed doors and windows, and other complications (fig. 22).

These soils have been studied by Hart (1974) under an investigation jointly funded by the Colorado Geological Survey and the U.S. Geological Survey as an element of the Front Range Urban Corridor program. Many of these soils have critically high potential swell pressures ("critically high" denotes pressures greater than about 15 t per square meter; Lambe, 1960, p. 20). Swelling is caused by sorption of water into or around the clay mineral crystal lattice. The mineral chiefly responsible is sodium montmorillonite, a clay mineral commonly dispersed in marine shales, in volcanogenic terrestrial deposits, and in weathered soil profiles in semiarid regions (Tourtelot, 1974, p. 266, 269). The material often called "bentonite" is nearly pure sodium montmorillonite. According to Tourtelot, pure sodium montmorillonite, rare in nature, might swell as much as 2,000 percent in volume. Some other clay minerals also have swelling properties but of less potential pressure.

Critically expansive soils on the Colorado Piedmont are most common on terrains underlain by Upper Cretaceous and Tertiary shales and mudstones, particularly in the widespread Pierre Shale and Denver Formation but also in several other formations. Many surficial deposits, such as alluvium and colluvium, moreover, and even eolian deposits may also have swelling properties, inherited from their parent formations (Hamilton and Owens, 1972a, table 2; Hart, 1974,

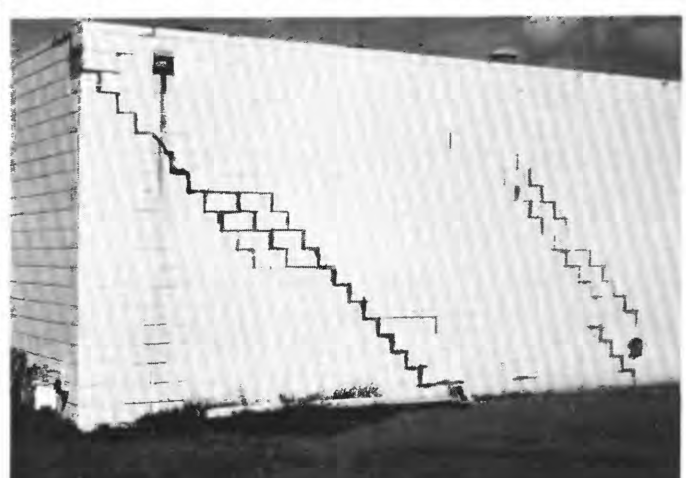

FIGURE 22.—Building wall damaged by stairstep corner fracturing, Lakewood, October 1976. The center section of the wall at right has been uplifted relative to the corner at left. Damage of this sort is frequently caused by expansive clay.

p. 6). Because of the wide areal distribution of these formations on the Colorado Piedmont, expansive soil is one of the most prevalent and costly geologic problems in the Front Range Urban Corridor. Ironically, soil expansion and its consequences are little known to the general public.

The potential volume change of a soil sample in the laboratory is only one measure of its possible behavior under field conditions on the Colorado Piedmont. The availability of moisture at the field site, the freedom of moisture to enter into the soil, the extent of alternate wetting and drying, soil density, and engineering design are equally important. Geologic materials that contain high-swelling clays also are very susceptible to slope failure, inasmuch as swell potential, plasticity, and shear strength tend to be interrelated. An approach to understanding expansive soils on the Colorado Piedmont has to be based on geologic studies, soil sampling and testing, case histories, evaluations, and engineering design.

LAND DEVELOPMENT ON EOLIAN SOILS

Loess and windblown sand cover much of the Colorado Piedmont, particularly leeward (east and southeast) of the flood plains of the major streams. These deposits, because of their physiographic and economic implications, have been under detailed study by the U.S. Geological Survey, but a better understanding than we now have of their regional physical settings and histories is needed to permit intelligent judgments about their place in land use planning and development. Loessial areas are among the best agricultural lands in the region, because of their good tilth, favorable moisture retention, and general fertility. Areas underlain by eolian sand, on the other hand, mostly lack these desirable attributes; as agricultural lands, they are used mostly for pastures.

Engineering properties of the eolian deposits are well understood in a general way (Larsen and Brown, 1971, tables 6–7, for example) and have been intensively investigated locally by the Colorado Division of Highways, the U.S. Geological Survey (Shroba, 1977), and by private engineering firms, but they are not well documented regionally. We are familiar with the general areal distribution of the deposits, but we know little about their thickness, textural variations, or field performance.

Like most underconsolidated soils, loess tends to subside under load, particularly when wetted (Holtz and Gibbs, 1952, p. 15) as, for example, in a new subdivision when new lawns and foundation plantings are being irrigated by homeowners, or when water from roofs is concentrated by downspouts. Susceptibility to subsidence depends partly on void ratios and on cementation; it may be slight or may be great enough to damage footings, foundations, sewer pipes, curbings, and heavily loaded floor slabs (Tabor, 1969, p. 53). Loess also is highly vulnerable to erosion by wind and running water when it has been stripped of its protective vegetation cover, either by agricultural practices or by urban land development (Larsen and Brown, 1971, p. 3, 16).

The loess and eolian sand of the Colorado Piedmont are related genetically and they grade into one another, but they differ markedly in physical properties and in response to disturbance. Eolian sand forms thin, blanketlike deposits and thick linear dunes, especially east of the South Platte River. Its signature on aerial photographs is distinctive and easily recognized (fig. 23). The linear dunes trend mostly from northwest to southeast. Broad areas east and south of Greeley, east of and in the eastern part of Denver, and east of Colorado Springs are blanketed with sand (Scott and Wobus, 1973; Shroba, 1977; Colton, 1978). In this semiarid region, eolian sand takes and transmits water readily but desiccates rapidly at the ground surface and supports thinner vegetation than most other soils. It is exceedingly fragile in an ecologic sense, therefore, and it recovers slowly from disturbance. Some dune areas that reportedly were reactivated during the dust bowl days of the 1930's have not yet regained stability (R. B. Colton, oral commun., 1974). Active deflation blowouts southeast of Greeley are visible from aircraft. In the Englewood area old barbed wire fences are partly buried south of Windsor Lake (Shroba, 1977).

Most of the dune sand supports grass, which deters wind erosion unless it it broken up by deep plowing or other land use. Once disturbed, the sand is vulnerable to erosion by wind and running water until a protective cover is restored. Both deflation and deposition, therefore, are problems around new land developments.

Because of very low shear strength, eolian sand is unstable and, on steep-cut slopes and unsupported open trenches, it may collapse without warning. Lives of workmen have been lost in such collapses in the Denver area. Dune sand also tends to settle under load, enough at times to damage rigid structures, particularly if it is subject to vibration (Tabor, 1969, p. 54).

SOILS CONTAINING ORGANIC MATTER

Soils rich in organic matter are relatively uncommon on the Colorado Piedmont, in terms of total area, because their development has been restricted by the semiarid climate. They are fairly widespread, however, on silty, alluvial bottomlands along stream valleys and other geomorphic settings where drainage is sluggish or poor. Piney Creek Alluvium and the modern flood plain, for example, are settings where such soils are prevalent (Hunt, 1954, p. 114, 117; Gardner and

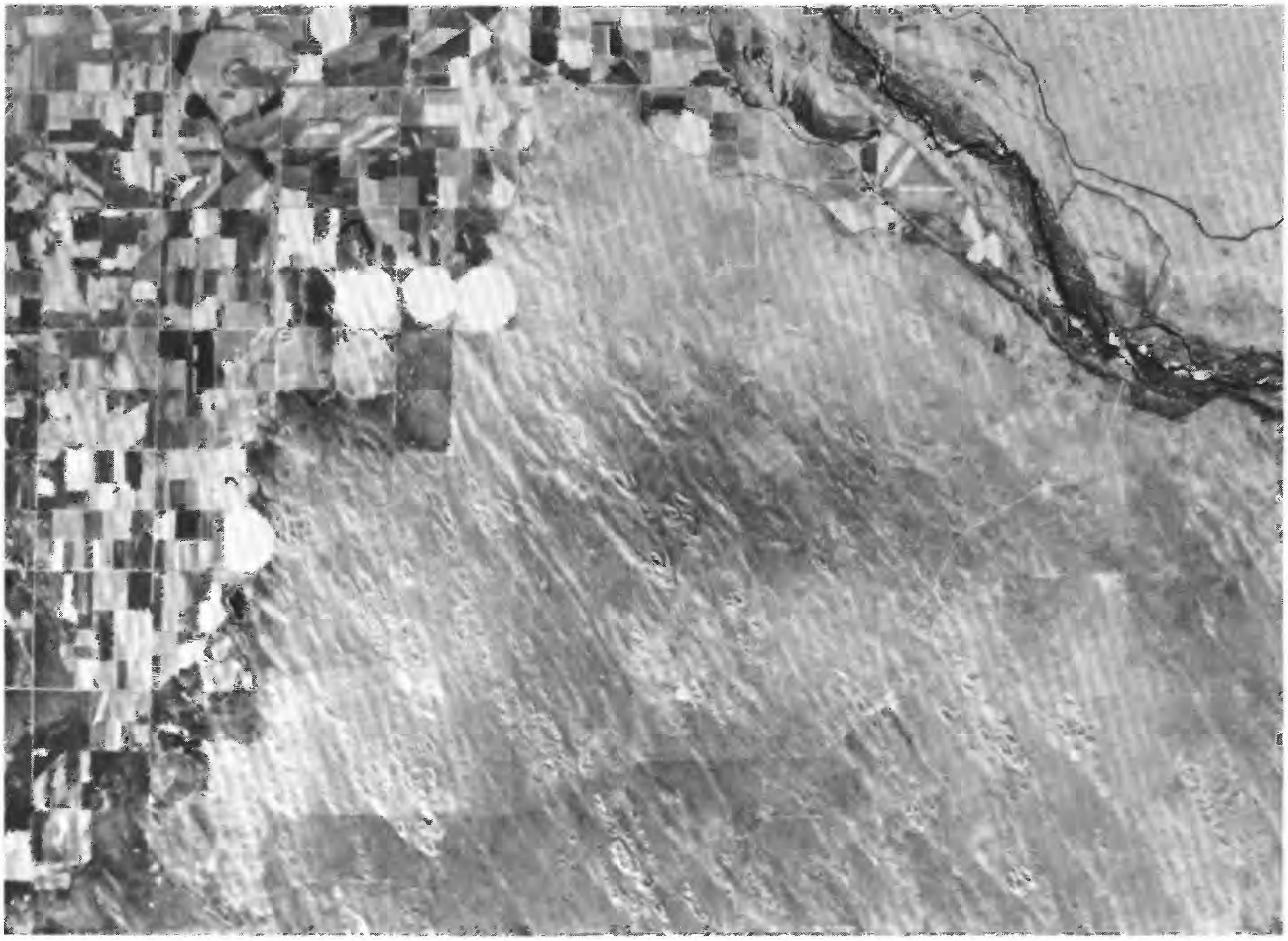

FIGURE 23.—Inactive dune field southeast of Greeley. North is at top of photograph. Strong linear trend is parallel to direction of depositing winds (northwest). Crescentic dunes contain small active blowouts. Unsuited for cultivation, this area is open range. Cultivated fields on loess are at left. South Platte River is in upper right. Scale is indicated by grid pattern of section-line roads at 1-mile intervals. High-altitude aerial photograph by National Aeronautics and Space Administration, October 26, 1972.

others, 1971, sheet 4; Scott, 1972d; Van Horn, 1972; Trimble, 1975; Shroba, 1977). Because of their compressibility and nonuniformity, organic soils are likely to settle under load, which can lead to structural damage of building foundations or road subgrades.

MOUNTAIN SOILS AND BEDROCK

The suitability of mountain areas for homesites, roads, underground-utility corridors, waste-disposal sites, and ground-water recharge depends partly on the thickness and character of the soil (in the engineering sense). Whether or not a utility trench can be dug with a backhoe, or whether more costly excavation procedures such as drilling and blasting are required, might determine the feasibility of a particular use for a given tract of land.

Residential expansion in the foothills of the Front Range, moreover, has been accompanied by problems of water supply and waste disposal (Hofstra and Hall, 1975a, b). The quantity of water available is small in many areas. Waste disposal and its effect on quality of water are influenced by the varied thickness of soil—both residual and transported—over crystalline bedrock and the varied filtration properties of mountain soils. Adequate soil thickness and percolation properties are essential for many uses of mountain tracts.

Recent work by the U.S. Geological Survey (Schmidt and Pierce, 1976) has outlined the distribution, thickness, and character of the mountain soils in the Front Range Urban Corridor as they relate to urbanization. This work was based on regional geomorphic relationships, field reconnaissance, well inventories, seismic profiling, and aerial-photograph interpretations. The soils include residuum and transported alluvium-colluvium (fig. 24). The thickest and most continuous deposits have developed under old, well-defined, upland erosion surfaces (pediments) that began to form as early as late in Eocene time (Scott,

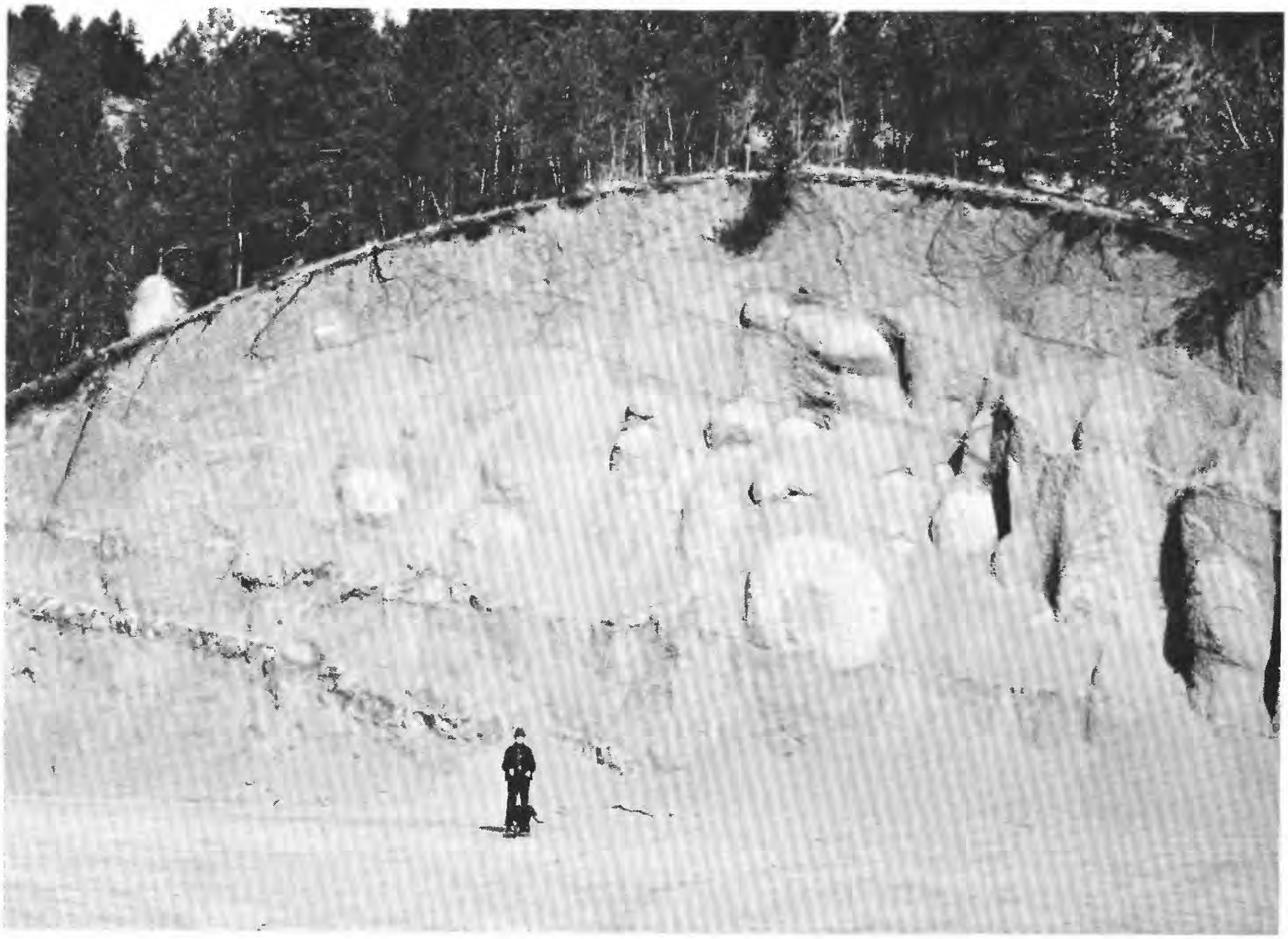

FIGURE 24.—Deeply weathered grus, Colorado Highway 67 west of Colorado Springs, formed on Pikes Peak Granite and containing fresh, hard core stones of granite. Easily excavated grus is widely used in the Front Range for road surfacing and earth fill. April 1972.

1975, p. 227). The characteristics of these saprolitic soils are related to parent material as well as to age; some of the thickest and most completely saprolized ones have developed on granitic terrains— underlain by Pikes Peak Granite or Boulder Creek Granodiorite, for example (Schmidt and Pierce, 1976, p. 46). Alteration and, hence, soil formation are very intensive also on wide, shattered fault zones but are minimal on quartzose gneiss or pegmatite (Schmidt and Pierce, 1976). The physical properties of the mountain soils, thus, are highly varied, and because of the growing pressure of mountain urbanization, the character of the mountain soils has increasingly concerned the planner and land user.

MASS WASTING

As used here, the term "mass wasting" refers to processes by which large masses of earth or rock are moved downslope by gravity. It excludes movements where water is the primary transporting medium, although water nearly always is involved in mass wasting. In the Front Range area mass wasting includes many kinds of landsliding and other types of movement such as soil creep and solifluction (fig. 25). The overturning of a concrete retaining wall is an effect of soil creep.

In the last few years, growth along the Front Range Urban Corridor has pushed urbanization into areas where mass-wasting processes impinge on urban land use. Construction of roads and dwellings has accelerated greatly in the foothills belt, where landslides, mudflows, soil creep, and rockfalls have been natural occurrences since prehistoric time. The foothills area, however, is attractive for residential development because of its scenic setting and its broad vistas of mountains and plains. It is fragile in a physiographic sense because of its semiarid climate, steep slopes, thin soils, abundant plastic shales and mudstones, steep dips of bedding, foliation, and joints, and slow recovery of vegetation in areas of disturbance. Care in site selection and treatment in these places can minimize adverse geomorphic effects.

FIGURE 25.—High plasticity of clay-bearing rocks promotes soil creep in the Laramie Formation, Jefferson County, near Interstate 70. Outcrop is topped with spoil from a nearby clay pit. June 1971.

Mass wasting along the Front Range is restricted mostly to clearly defined geomorphic settings where problems have a rather high element of predictability. In a series of pilot studies, the U.S. Geological Survey has published maps that show particular types and areas of concern including, for example, landslides, rockfalls, swelling soils, and flood-prone areas (Maberry, 1972a; Scott, 1972a, b, c; Simpson, 1973a; Colton and Holligan, 1977). Regional maps showing landslides have been prepared by Colton and others (1975), Colton, Holligan, and Anderson (1975a, b), and Crosby (1978).

Mass wasting is a response to the pull of gravity. Resistance is most often overcome by the introduction of water into soil or rock. Freezing and thawing may loosen and dislodge material, freeing it to slide or fall. Saturation by heavy or prolonged rain or by melting snow may induce failure, partly by reducing the shear resistance of the mass and partly by increasing the shear stress through the added weight of the water (fig. 26). Many small landslides followed the prolonged rains of May 5–6, 1973, in the Greater Denver Area (Hansen, 1973, p. 11–17). Earthquakes may cause instantaneous failure of material, wet or dry, both by reducing shear resistance and by increasing shear stress. A large rockfall at the foot of Cheyenne Mountain south of Colorado Springs may have been triggered by a prehistoric earthquake (Scott and Wobus, 1973).

Mass wasting is a problem in the Front Range Urban Corridor chiefly in hilly terrains underlain by Upper Cretaceous and Tertiary shale and mudstone of the Dakota Group, Benton and Pierre Shales, Laramie and Denver Formations, and Dawson Arkose. These formations underlie broad areas in the path of urbanization. Nearly every formation in the geologic column, however, is involved in slope failure somewhere in the area. Scores of small landslides and mudflows were set off in the storm of May 5–6, 1973 in the formations cited above and also in the Lykins and Morrison Formations and weathered parts of the Precambrian rocks. Most of these failures were in disturbed areas where slopes had been oversteepened or unbalanced by hillside excavations such as roadcuts. Proposed excavations in hillside locations, therefore, should be evaluated for evidence of past slope instability, for evidence that the materials involved have a record of poor field performance, or for indications that an excavation might precipitate a slope failure.

HYDROLOGY

Urbanization has interacted with the hydrology of the Front Range Urban Corridor, and the effects have influenced the lives and fortunes of the populace. Urbanization has increased peak flows of streams following storms, decreased mean flows, and altered the frequency and magnitude of floods. It has affected channel characteristics, scour and sedimentation, ground-water conditions, and water quality. These combined effects cause ecologic changes in the streams and their surroundings and alter the esthetic values of the area—what Leopold (1968, p. 1) has called the "hydrologic amenities . . . the impression which the river, its channel and its valleys, leaves with the observer. Of all land-use changes affecting the hydrology of an area, urbanization is by far the most forceful."

FIGURE 26.—Rockfall on eastbound Interstate 70, 3.2 km west of Bergen Park interchange, triggered by heavy rains of May 5–6, 1973. Oversteepened rock cut failed along joints and foliation planes. Photographed May 8, 1973 after preliminary cleanup had removed rock from lanes of traffic.

Continued urban growth on the Colorado Piedmont has intensified hydrologic problems that have been recorded since pioneer days (Hansen, 1976, p. 100). A large part of the U.S. Geological Survey's work in the Front Range Urban Corridor, therefore, has been directed toward the hydrologic aspects of land use on the Colorado Piedmont. The availability of hydrologic data for the corridor published by the U.S. Geological Survey and cooperating agencies is summarized by Hampton, Clark, and McNutt (1974), Hampton (1975), and Anna (1975). Convenient sources of bibliographic information through 1970 have been compiled by Pearl (1971) and through 1972 by Chronic and Chronic (1974). Persons interested in specific areas or subjects not listed in these sources or published more recently should contact the U.S. Geological Survey, Denver, or the Colorado Department of Natural Resources for assistance and information.

FLOODING

Accounts dating back more than 150 years, and even farther in Indian legend, indicate that intense rainfall and severe flooding can be expected from time to time along all major tributaries of the South Platte and Arkansas Rivers in the Front Range and on the Colorado Piedmont (Follansbee and Sawyer, 1948; Jenkins, 1961, 1963, Matthai, 1969; Ducret and Hansen, 1973; Hansen, 1973; McCain and Hotchkiss, 1975a, b, c). Early flood warnings—mostly unheeded— were given by the 19th-century Indians to the settlers, and much grief might have been forestalled had the warnings been heeded more often. Episodic flooding is perhaps the foremost natural hazard in the Front Range Urban Corridor area. Record discharges of selected streams are listed in table 3. These streams, and many others of the area, have histories of repeated catastrophic flooding (figs. 27 and 28).

Of great importance to land-use applications, therefore, has been the portrayal of flood-prone areas in the corridor by maps and reports, including published synoptic maps at a scale of 1:100,000 (McCain and Hotchkiss, 1975a, b, c) and open file maps of numerous, more detailed $7\frac{1}{2}$-minute quadrangles at a scale of 1:24,000. Flood-plain information for the streams and gulches in the Denver metropolitan region also has been prepared by the U.S. Army, Corps of Engineers, Omaha, Neb., for the Denver Regional Council of Governments.

Floods on the South Platte and Arkansas Rivers and their Front Range tributaries generally result from intense rainfall of short duration and are characterized by uncommonly high velocities and short durations, owing to a combination of unusual physiographic and climatologic factors. Streams of the area are adjusted to regimens of relatively small mean flows in channels with relatively steep gradients, particularly as compared with streams of similar drainage area in more humid, less elevated regions of the United States. Low relative humidity and high evapotranspiration rates tend to reduce infiltration and soil moisture, resulting in relatively sparse vegetation and humus-poor soil over much of the area, which further favor low infiltration and rapid runoff during intense cloudburst storms. Consequently, the ability of Front Range streams to transport sediment, rocks, and debris is increased enormously during floods.

Channel changes along most perennial streams are accomplished principally by occasional flows near or above bankfull stage (Leopold and others, 1964, p. 82–84; Leopold, 1968, p. 7). Channels, therefore, tend to be adjusted to such discharges. Infrequent devastating floods accelerate bed and bank erosion, overbank scour and sedimentation, sheetflooding, and mass wastage.

The regional rise of the Great Plains toward the Rocky Mountains and the physiography of the Front Range itself constitute an orographic barrier that markedly affects the distribution and intensity of storms. Intense shower activity is favored by the upslope flow of warm, moist air from the Gulf of Mexico or from the Pacific Ocean, held in close to the mountains by easterly circulation aloft.

Historic floods in the Front Range area have been restricted largely to the months of May through September (Hansen and others, 1978, fig. 8). The time distribution of Front Range floods is distinctly bimodal, with peaks in the first week of June and the first week of August. Late spring and early summer floods often have been caused by a combination of rapid melting of mountain snowpacks and regional rainstorms. Other late spring and early summer floods, and nearly all late summer floods, on the other hand, have resulted exclusively from intense local thunderstorms.

McCain and Jarrett (1976, p. 39–40) believed there is an upper altitude limit at which severe cloudburst flooding is likely in the Southern Rocky Mountains, owing chiefly to a reduced moisture supply available to thunderstorms at higher altitudes. In the Front Range area this limit is about 2,300 m in the South Platte River drainage and about 2,750 m in the Arkansas River drainage. Past flooding in the Front Range seems to prove this conclusion; the upper limit of locally intense flooding accompanying the July 1976 storm over the Big Thompson Canyon area was about 2,550 m (McCain and others, 1979; Shroba and others, 1979).

Astonishing precipitation rates have accompanied some of these storms (Follansbee and Sawyer, 1948, p.

FIGURE 27.—Damage caused by the June 15-16, 1965, flood in Denver, Colorado. Water mark on building is at level of the top of the 10th cinderblock. Photograph by Warren B. Hamilton.

70; Matthai, 1969, p. B3, B12; Maddox and others, 1977). On May 30, 1935, for example, 610 mm of rain fell in 1 day, most of it in about 3 hours, at Elbert, 70 km southeast of Denver (Follansbee and Sawyer, 1948, p. 70). On June 16, 1965, more than 350 mm fell in about 4 hours at Palmer Lake, 65 km south of Denver (Matthai, 1969, p. B14), and comparable amounts fell on several nearby areas. During the tragic Big Thompson Canyon storm of July 31-August 1, 1976, more than 150 mm of rain fell at Glen Comfort in 45 minutes, and 250 mm fell in less than 4 hours (L. R. Hoxit, written commun, 1977).

Downpours such as these generally are very localized and commonly trigger flash floods that may exceed normal discharge by two or three orders of magnitude. Matthai (1969, p. B17-B18) estimated that East Plum Creek, about halfway between Palmer Lake and Denver, increased its volume a thousandfold in less than 3 hours during the 1965 storm and attained a

FIGURE 28.—Flooding at East Jefferson Avenue and South Emerson Street in Englewood, caused by overflow of Little Dry Creek. Denver Post photograph by John Prieto, May 6, 1973.

TABLE 3.—*Record discharges of selected streams, Colorado Piedmont area,*
[Data from U.S. Geological Survey, 1969]

Stream	Date	Peak discharge (ft^3/s)[1]
South Boulder Creek at Eldorado Springs	Sept. 2, 1938	7,390
Bear Creek at Morrison	July 24, 1896	8,600
Clear Creek at Golden	Aug. 1, 1888	8,700
St. Vrain Creek at Lyons	June 22, 1941	10,500
St. Vrain Creek at Platteville	Sept. 3, 1938	11,300
Buckhorn Creek at Masonville	Aug. 3, 1951	14,000
Cache la Poudre River at Fort Collins	Mar. 20, 1904	21,000
Fountain Creek at Security	July 24, 1965	25,000
Big Thompson River at mouth of canyon[2]	July 31, 1976	31,200
South Platte River at Denver	June 17, 1965	40,300
Cherry Creek at Cherry Creek Lake	June 16, 1965	59,000
South Platte River at Littleton	June 16, 1965	110,000
Kiowa Creek north of Kiowa	May 31, 1935	110,000
Plum Creek at Louviers	June 16, 1965	154,000
Bijou Creek near Wiggins (east of Roggen)	June 17, 1965	466,000

[1] Discharge measurements customarily are made in ft^3/s (cubic feet per second). One ft^3 equals 0.02832 m^3 (cubic meter).
[2] McCain and others, 1979, table 3.

maximum velocity of 6.1-6.7 m/s (meters per second). McCain and others (1979) calculated that the Big Thompson River, during the 1976 storm, attained a velocity of nearly 8 m/s at the mouth of its canyon.

The enhanced capability of Front Range streams to modify the landscape at floodstage, therefore, is hardly surprising. Water at such velocities can move huge objects. What is suprising, even in full knowledge of the semiaridity of the climate, is the slow natural recovery of the landscape, and the effect, therefore, of flooding on the visual amenity (Hansen, 1976, p. 90). Many of the hillside and channel scars from the 1965 storms are little changed after 14 years (fig. 29). Gullying caused by a 220 mm downpour in Mount Vernon Canyon in the Front Range west of Denver in 1938 was still plainly visible in 1978.

The Big Thompson Canyon flood of 1976 is remembered by many Colorado citizens, partly because of its tragic death toll and partly because of its magnitude. This was the largest historic flood in the Big Thompson River basin, having exceeded any previous historic flood there in rate of discharge by at least a factor of two and in the canyon by a factor of four. Although the flood was exceptional, it was not unique to the Front Range. Many comparable floods have been recorded in other basins along the Front Range in the past century or so, and in terms of total runoff, rate of discharge, and property damage, some of these have been much larger. Before 1976, the largest recorded discharge on the Big Thompson River at the mouth of the canyon was 7,600 ft^3/s (cubic feet per second) on July 19, 1945, a rate comparable to historic maxima on Bear Creek, Clear Creek, and South Boulder Creek. In comparison Buckhorn Creek, a tributary of the Big Thompson River, discharged 14,000 ft^3/s in 1951.

Geomorphic evidence supports the certainty of past and projected future catastrophic flooding along Front Range streams. Most canyons along the Front Range are physiographically similar and have had parallel hydrogeologic histories. Nearly all Front Range canyons in the lower montane zone (upper altitude limit about 2,400 m) contain evidence of intense channel scour in recent time. Historic evidence includes destroyed segments of roads and railroad grades. Large debris fans also are common in nearly all canyons in the lower montane zone, and they are clearly the products of torrential runoff. Some of them have been modified by historic flash flooding. Morphologically they are close counterparts of fans that were formed or modified during the 1976 flooding in Big Thomp-

FIGURE 29.—Debris-avalanche scar photographed in December 1972 on Hunt Mountain, 11 km south of Castle Rock, caused by torrential rains of June 15–16, 1965, and little changed at the time of this report (1979). Hunt Mountain is capped by Castle Rock Conglomerate, and scar is eroded into the Dawson Arkose.

son Canyon. Finally, the channels of most Front Range streams contain bouldery flood gravels similar to those transported and deposited by the Big Thompson flood of 1976.

URBANIZATION AND RUNOFF

The effects of urbanization on runoff have been studied by many investigators in recent years. Leopold (1968, p. 1) has listed four interrelated but separable effects of land-use changes that can be applied to Front Range streams: (1) changes in peak flow, (2) changes in total runoff, (3) changes in water quality, and (4) changes in the hydrologic amenities. His figure 1 shows that peak discharge rises higher and arrives sooner after urbanization than before and that the volume of runoff increases proportionally. Conversely, infiltration and ground-water recharge decrease, thus reducing base flow and lowering the water table. Consequently, stream flow after urbanization is higher during and just after storms and is lower at other times. Moreover, the exposure of bare ground to storm runoff during urban construction increases the sediment yield, which also alters runoff characteristics and clogs drainage channels (Guy, 1970, p. E3). Urban refuse, such as rubber tires, beer cans, paper cartons, detergents, fertilizers, and countless other wastes picked up during storms or carelessly dumped into water courses, degrades the hydrologic amenity,[2] degrades the quality of the water, and disrupts the living processes of aquatic organisms. Along Cherry Creek, for example, a general downstream degradation in water quality from Franktown through Denver has been documented by Costa (1978, table 14).

Human activities along the Front Range Urban Corridor have accelerated ongoing hydrogeomorphic pro-

[2] Leopold (1968) defined the hydrologic amenity as the overall impression that the stream-and-valley system makes on the reservoir.

cesses. Prolonged rains—not of the cloudburst type—on May 5-6, 1973 caused about $50 million damage through inundation, scour, sedimentation, landsliding, and mudflowage (Ducret and Hansen, 1973; Hansen, 1973). Much of the damage from this storm was in areas where manmade modification of the terrain had altered the runoff characteristics. Constraints on the free flow of runoff were caused by bridges, culverts, channel constrictions and flood-plain encroachments. Peak flows were accentuated by total runoff from impervious roofs, driveways, streets, and parking lots. Water was retained behind many culverts and storm drains that were designed to pass smaller flows. Irrigation ditches overflowed with water intercepted from usually dry gulches. Sheetflooding was aggravated by the practice of stripping vegetation and soil from building sites and tracts during land development. Most of the many observed landslides, mudflows, and rockfalls caused by this storm were in places where support had been removed from previously stable hillslopes. The extensive damage resulting from this storm indicates the need for carefully planned land development in areas where geomorphic processes are active or are likely to be activated.

GROUND WATER

Many reports dealing with the ground water resources of different parts of the Front Range Urban Corridor and adjacent areas have been prepared in the past few years by the U.S. Geological Survey, and by the Colorado Department of Natural Resources. Much of the following information is summarized from these reports.

VALLEY-FILL ALLUVIUM

Important alluvial aquifers underlie the valleys of all the principal streams of the Colorado Piedmont (Smith and others, 1964; Hershey and Schneider, 1964; Hurr and others, 1972a, b; Bingham and Klein, 1973; Hurr and others, 1975; McConaghy and others, 1964; Hillier and Schneider, 1979a, b; Hillier and Hutchinson, 1980a, b). The water from these aquifers is widely used in households and for irrigation in rural areas, either to supplement or to supplant surface-water sources (Code, 1943). The water also is used to some extent for municipal supplies (Hurr and others, 1975, p. 2, 4), although most urban areas rely mainly on surface water from mountain sources for municipal uses.

Valley-fill alluvium in the South Platte River valley, according to Hurr, Schneider, and Minges (1975, table 1), yields 380 to 9,000 L/min (liters per minute) to irrigation wells, and concentrations of dissolved solids range from about 200 to 1,600 mg/L (milligrams per liter) (Hillier and Schneider, 1979b; Hillier and others, 1979). The water ranges from moderately hard to very hard and contains excessive (more than 250 mg/L) sulfate concentrations. Water suitable for use as a drinking-water supply occurs from Kassler to Littleton (Hillier and others, 1979).

In addition to the tremendous ground-water reservoirs in the fills of the major stream valleys, large reservoirs occupy buried segments of old stream channels abandoned as a result of Quaternary drainage changes during the gradual evolution of the present drainage pattern. One such buried valley, averaging 1.5-3 km in width, lies beneath Beebe Draw and its extensions north and south, a total extent of perhaps 55-60 km. Beebe Draw is about 8-10 km east of the present valley of the South Platte River between Brighton and Platteville. Northward continuations of the buried valley pass beneath Milton and Lower Latham Reservoirs (Colton and Fitch, 1974). This buried valley apparently is an abandoned segment of the old Pleistocene valley of the South Platte River. It was abandoned when the South Platte was diverted by stream capture by a tributary of the Cache la Poudre River (Smith and others, 1964, p. 32, 33). The valley fill beneath Beebe Draw is as much as 24-30 m thick, and depth to the water table ranges from about 1 to 14 m below the ground surface (Hillier and Schneider, 1979a). The water is used extensively for crop irrigation. Dissolved-solids concentrations range from about 700 to 2,300 mg/L and locally the water contains excessive sulfate (more than 250 mg/L) concentrations (Hillier and Schneider, 1979b; Hillier and others, 1979).

A less well delineated buried valley trends northward through east Denver from the valley of Cherry Creek at about Monaco Street toward Sand Creek. This valley is an abandoned former course of Cherry Creek captured by a tributary of the South Platte River that is now the present Cherry Creek. As much as 26 m of clean, pebbly, saturated sand underlies 1.5-6 m of eolian material (Shroba, 1977, p. 5). This reservoir is largely untapped.

PEDIMENT GRAVELS

A detailed study by Hurr (1976) of the hydrology of the alluvial gravel at and adjacent to the Rocky Flats nuclear processing plant provides a basis for making inferences about the hydrologic characteristics of other gravel deposits that cap pediments elsewhere along the Colorado Piedmont. These so-called pediment gravels were laid down at various times during the Pleistocene Epoch by streams that deposited sediment at the foot of the mountains in response to reduced gradients and carrying capacities. The pediment gravels are mostly coarse and poorly sorted and contain admixtures of alluvial and eolian sand and silt. Overall, they diminish in grain size away from the mountains.

Ground water in these deposits is recharged from rain, snowmelt, and surface water sources. Infiltration rates and permeability are variable: Hurr (1976, p. 18) cited rates in the Rocky Flats Alluvium that ranged from 5-150 mm/h (millimeters per hour) in the upper 1.5 m of soil to 99-187 mm/h in stony soil. Comparably wide ranges are likely in other alluviums such as the Verdos and Slocum. The local water tables fluctuate in response to seasonal variations in precipitation, stream flow, and irrigation, and they vary markedly from place to place (Hillier and Schneider, 1979a; Hillier and Hutchinson, 1980a). The water is mostly hard, because most of the deposits contain strongly developed Cca (calcium carbonate) soil horizons (Scott, 1963; Colton and Fitch, 1974; Trimble and Fitch, 1974a, b; Machette, 1977). Water is suitable for drinking in some of these deposits (Hillier and Schneider, 1979b; Hillier and Hutchinson, 1980b).

Some pediment deposits of the area yield sufficient water for irrigation (for example, several hundred to about 2,000 liters per minute). Isolated pediment remnants high above present drainage and away from sources of recharge, however, are apt to be drained of ground water (Hershey and Schneider, 1964, p. X14; Smith and others, 1964, p. 58; Hillier and Schneider, 1979a; Hillier and Hutchinson, 1980a).

TERRACES

Gravel terraces of late Pleistocene and Holocene age along the major stream valleys of the Front Range Urban Corridor yield water of varied but commonly suitable quality and volume for crop irrigation. The quality of some water is suitable for municipal and industrial use also (Hershey and Schneider, 1964, p. X14, X20; Smith and others, 1964, p. 59, 107; Bingham and Klein, 1973, table 1; Hillier and Schneider, 1979b; Hillier and Hutchinson, 1980b; Hillier and others, 1979). The broad terraces of the South Platte River downstream from Denver, the Cache la Poudre River near Fort Collins and Greeley, and Fountain Creek downstream from Colorado Springs all are extensive ground water reservoirs. The above-cited authors noted that the specific conductance and, hence, the dissolved solids in the water, increases generally downstream. Generally, the quality of water in terraces is most suitable for uses associated with urban development in the Colorado Springs—Castle Rock area and least suitable in the Boulder—Fort Collins—Greeley area (Hillier and Schneider, 1979b; Hillier and Hutchinson, 1980b; Hillier and others, 1979).

Beneath some terraces the ground water is continuous with that in the subjacent valley fill. In such physiographic settings, the terrace and the valley fill commonly are formed from the same body of gravel. But in some other terraces the water is perched on impervious rocks, and water issues from the terrace margins as seeps or springs (Smith and others, 1964 p. 109).

EOLIAN SAND

Where saturated, eolian sand locally yields water containing less than 500 mg/L of dissolved solids (Hurr and others, 1975, table 1). Dune areas afford excellent infiltration for recharge because they absorb precipitation readily with minimal runoff. In some places in the eastern parts of the Greater Denver Area, where eolian sands overlie relatively impermeable rocks, marked rises in the water table have accompanied increased irrigation of yards in new neighborhoods. Locally, this rise has caused flooding in basements that previously were dry (Hamilton and Owens, 1972b, p. 329).

BEDROCK AQUIFERS

Water has been produced for many years from bedrock aquifers in the Denver Basin beneath the Colorado Piedmont (Emmons and others, 1896, p. 402). In recent summary description of these aquifers, Romero (1976, p. 101) stated that "The bedrock aquifers of the Denver Basin contain vast quantities of ground water suitable in most localities for all beneficial purposes. If managed with caution, the basin can supply the water needs of several generations." Well yields generally are sufficient for household, livestock, and industrial uses, but commonly are insufficient for crop irrigation. Many wells yield water under artesian conditions, but generally the pressure is not sufficient to cause water to flow from the ground (Chase, 1962; Romero, 1976, p. 56). Large withdrawals of water over the years, moreover, have greatly lowered the artesian head in some areas.

The most productive artesian wells obtain water from the Arapahoe Formation, and the Laramie-Fox Hills aquifers. Some wells completed in the Arapahoe

Formation yield as much as 1,500-1,800 L/min (Romero, 1976, p. 49). Commonly the yield is about 380 L/min. This water is a sodium bicarbonate type and is the least mineralized ground water in the area, except for some water from sand dunes (Hurr and others, 1975, table 1).

The Laramie-Fox Hills aquifer obtains water from the lower 45-60 m of the Laramie Formation and the underlying Fox Hills Sandstone. "Wells that fully penetrate the aquifer generally yield about 100 gal/min [380 L/min], and a few yield as much as 900 gal/min [3,400 L/min]. Water in the aquifer, at places, contains objectional amounts of methane, hydrogen sulfide, iron, and fluoride. In most places, the aquifer contains water of suitable quality for domestic use" (Romero and Hampton, 1972). Wells completed in sandstone beds in the upper part of the Laramie Formation in the Denver Basin generally yield only a few tens of liters per minute (Romero, 1976, p. 29).

In parts of the Greater Denver Area, sandstone beds and lenses in the Denver Formation, which overlies the Arapahoe Formation, provide water for household use and irrigation of lawns and gardens. Wells may yield a few tens of liters per minute. Much of the Denver Formation, however, contains too much clay to yield water. According to Hurr, Schneider, and Minges (1975, table 1), the water in the Denver Formation is a sodium bicarbonate type and total hardness generally is less than 60 mg/L.

The Dawson Arkose, which overlies and intertongues with the Denver Formation and also underlies parts of the Greater Denver and Colorado Springs–Castle Rock areas, contain water in sufficient quantities and of suitable quality for uses associated with urban development (Romero, 1976, p. 46-51, 76). Most water for Castle Rock, for example, is obtained from the Dawson (Romero, 1976, p. 76). The principal water-bearing interval consists of coarse, micaceous, arkosic sandstone in the lower 120-150 m of the formation. The upper 150-180 m also contains water-bearing strata, but they are less continuous and are thinner than those in the lower part of the formation. Few wells yielding more than 400 L/s have been drilled into the Dawson Arkose, and its yield capacity is not well known. Romero (1976, p. 51) suggested that sustained yields of 1,500 L/min probably can be obtained in the south-central part of the Denver Basin.

Aquifers in older Mesozoic and Paleozoic formations underlying the Colorado Piedmont generally are too deep for economic development of water supplies except on or near the outcrop in the immediate vicinity of the mountain front. At points more distant from the mountains, moreover, suitable water supplies generally can be obtained from younger rocks at shallower depths.

The pre-Pennsylvanian sedimentary rocks are not regarded by Romero (1976, p. 28) as being principal aquifers in most of the Front Range Urban Corridor, even though they may contain water. Outcrops of these rocks are largely restricted to a narrow discontinuous zone between Perry Park and Colorado Springs at the foot of the Rampart Range and to very localized exposures along the Ute Pass fault (Scott and Wobus, 1973). Away from the mountain front, these rocks are too deep to be seriously considered as sources of ground water.

The most significant aquifers below the Laramie-Fox Hills aquifer are in the Fountain Formation, Lyons Sandstone, and Dakota Group. Wells in both the Fountain and Lyons yield 6-240 L/min, with most yields being 18-36 L/min (Romero, 1976, p. 31).

Water in the Dakota Group is obtained near the outcrop from sandstone beds in the Lytle and South Platte Formations. Toward the east the depth to these beds increases rapidly and the quality of water deteriorates to the extent that the group can no longer be considered as a source of water. Wells completed in the Dakota Group yield an average of about 60 L/min (Romero, 1976, p. 32-34).

MOUNTAIN LAND DEVELOPMENT AND GROUND-WATER SUPPLIES

Many mountain residents rely on untreated well water for domestic supplies. Most of this water is obtained from fractures in the bedrock; the crystalline bedrock itself is virtually impervious. Vertical and lateral movement of water in the fractures is dependent on the size of openings, interconnections, and number of fractures extending to the land surface (Hofstra and Hall, 1975b).

Most mountain households also have individual septic-tanks and leach-field waste-disposal systems. The suitability of the mountain terrain for on-site waste disposal varies with the extent, thickness, and character of the soil overlying the bedrock (Schmidt and Pierce, 1976). Consequently, ground-water contamination is a serious problem in some mountain areas. Findings from a hydrologic and water-quality survey of western Jefferson County, Colo. (Hofstra and Hall, 1975a, b), which probably are representative of ground-water conditions in other urbanizing mountainous areas in the Front Range Urban Corridor, were: (1) ground-water contamination was common where one homeowner's leach field was upgradient from his own or his neighbor's well; (2) during wet seasons, especially on sloping ground, the water table rises locally to the ground surface, and inadequately treated waste water issues from the ground; (3) in some mountainous parts of Jefferson County, as many as 20 percent of the wells are contaminated with fecal-coliform bacteria; and (4) many wells contain nitrate, phosphorus, and chloride in excess of natural concentrations (Biesecker and others, 1973, p. 422).

LAKES

The hydrologic characteristics of lakes in the Front Range Urban Corridor are inventoried on maps by Ficke and Danielson (1973), Danielson (1975), and Adams (1976). These characteristics include surface area, shoreline length, specific conductance, pH, transparency of the water, and algal and chlorophyll concentrations. For a semiarid region, the Front Range Urban Corridor contains a surprising number of small lakes. Some are natural water bodies that have been enlarged by damming. Many are owned by private individuals, partnerships, or irrigation and ditch companies. Some lakes are owned by municipalities and are used for domestic water supplies. Some, such as Barr Lake near Brighton, are wildlife refuges. Many of the lakes now have multiple uses, and with increasing urbanization, uses are changing. Lakes enhance the value of adjacent property as they become centers of real-estate development and water-related recreation. The lake inventories, therefore, should be helpful in planning for the best future uses of these increasingly valuable resources.

SEISMICITY

The swarm of earthquakes that followed the injection of waste water into the deep disposal well at the Rocky Mountain Arsenal—the "Derby earthquakes" (Evans, 1966)—generated wide concern about potential earthquake hazards along the Front Range Urban Corridor. Algermissen's seismic risk map of the United States (Algermissen, 1969) places Colorado in category 1--minor damage, based on a statistical evaluation of past earthquake magnitudes, intensities, and strain releases. Frequency of occurrence was not a consideration in assigning ratings to the various risk zones of Algermissen's map, but Algermissen pointed out that one approach to the problem of determining relative seismicity of various regions is to plot earthquake magnitude versus frequency. If this approach were used, the relative seismicity of Colorado would have to be judged as low. Algermissen also noted that historical records do provide guidelines to relative seismicity, although the historic record for the United States is too short to adequately estimate recurrence rates for many areas. Geologic evidence of past earthquake occurrences, therefore, offers useful clues as to the probability of future earthquake activity that cannot be judged from historic occurrences alone.

Except for the Derby earthquakes related to the Rocky Mountain Arsenal disposal well, few earthquakes larger than MM (modified Mercalli intensity) III have been experienced in the Front Range Urban Corridor area in the 100 years of record. (Several of the Derby earthquakes exceeded MM IV, and the strongest attained MM VII and a Richter magnitude of 5.3; Hadsell, 1968; Major and Simon, 1968; National Oceanic and Atmospheric Administration, 1977, reported by Kirkham and Rogers, 1978, appendix 3). In 1882 an earthquake of MM VII was felt in Denver and in a wide surrounding area, including southern Wyoming, (Hadsell, 1968), but no natural occurrence of that intensity has happened since. Except for the artificially triggered Derby shocks, historic earthquake activity in the Front Range area has been infrequent and mainly of low intensity.

Some faults in the Front Range area displace deposits of Quaternary age with offsets that indicate earthquakes of Richter magnitudes 5 to 6 or more (fig. 30). Few earthquakes smaller than Richter magnitude 6.5–7 cause surface faulting, although smaller shocks occasionally cause ground ruptures through landsliding. Shallow-focused earthquakes of magnitudes less than 6 have caused surface faulting in California; an example is the Parkfield-Cholame earthquake of 1966. Also, ground breakage can be caused by tectonic creep without perceptible earthquakes. Scott (1970) has identified eight faults in east-central Colorado that have displaced Quaternary deposits. Three of these in the Front Range area have displaced gravels correlated by Scott with the Verdos Alluvium, which has an age of about 0.6–0.7 m.y., equivalent to the Yarmouth Interstadial. A movement of the Golden fault had been bracketed in time between the Yarmouth and Sangamon(?) Interstadials (Kirkham, 1977, p. 692). Because no offset has been found in the Front Range area in deposits younger than Sangamon(?) age (about 125,000 years ago), the frequency of earthquakes strong enough to cause ground breakage along the Front Range has been very low.

Despite the low frequency of past events, the possibility of large earthquakes in the future cannot be discounted. Many Front Range faults have very long histories of recurrent movements, some dating back to Precambrian time. The large total displacements of some of these faults in Neogene (Miocene and Pliocene) time (Epis and Chapin, 1975; Taylor, 1975; Scott, 1975) and the relatively short geologic time since last movement compared to the total period of activity suggest that further Holocene movements are probable.

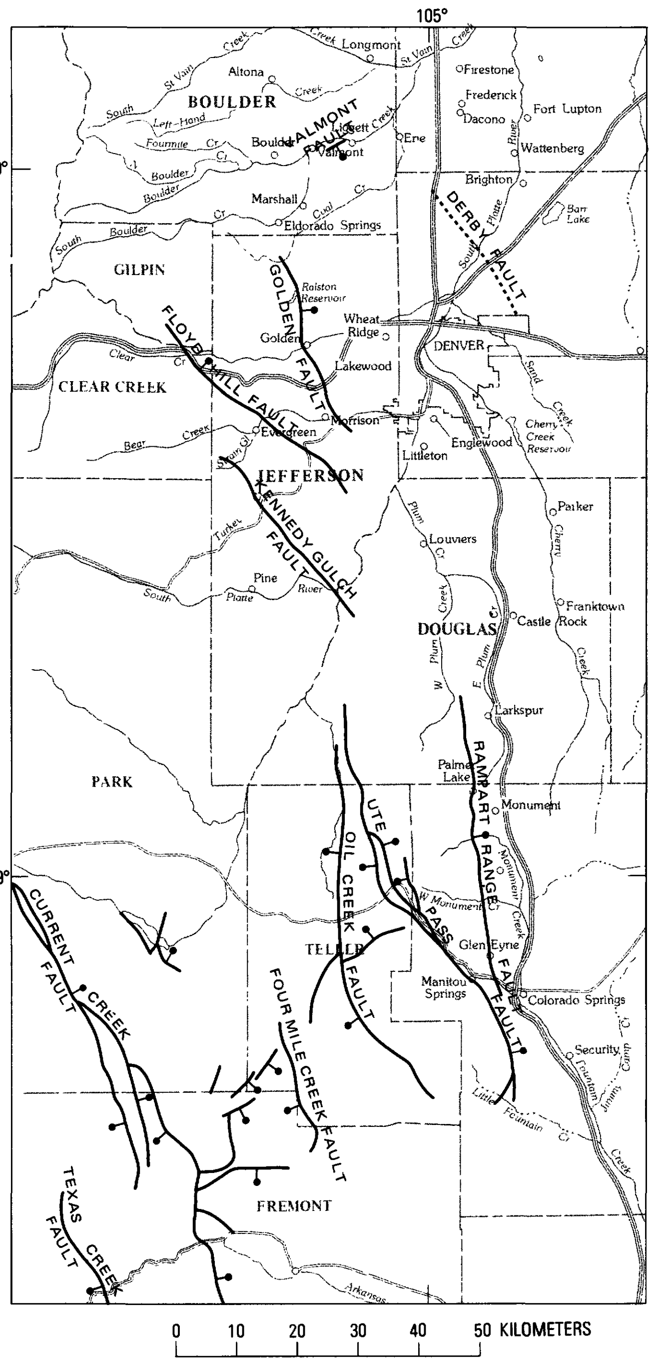

FIGURE 30.—Map showing traces of known Quaternary faults in the Front Range and adjacent areas. Bar and ball are on downthrown side. Dotted fault is deeply buried and inferred. From Kirkham and Rogers, 1978.

Matthews (1973, p. 111) has even suggested a reevaluation of Colorado's seismic-risk classification and a building code that embodies an earthquake-resistant design, arguing that 100 years of record is insufficient to establish a realistic measurement of earthquake recurrence in the Front Range area.

To learn more about the distribution of potentially active faults in the State, the Colorado Geological Survey has restudied Colorado seismicity (Kirkham and Rogers, 1978) in a project jointly funded by the U.S. Geological Survey as an element of the Front Range Urban Corridor program, with the objective of applying the information gained to a reappraisal of seismic risk and to an evaluation of the risk impact on land-use planning. R. M. Kirkham and W. P. Rogers (written commun., 1978) believe that the seismic-risk potential of Colorado in general and of the Front Range Urban Corridor in particular is greater than the historic record of seismicity indicates. The recurrence intervals of some geologically indicated seismic events have been much longer than the historic record.

PHYSICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS OF SURFICIAL DEPOSITS AND ROCK UNITS IN THE GREATER DENVER AREA

By RALPH R. SHROBA

INTRODUCTION

The Front Range Urban Corridor encompasses a wide array of surficial deposits and rock units of contrasting physical properties and performance characteristics that influence the suitability of the land for varied urban development. General information pertaining to the properties and characteristics of the materials at and near the surface therefore is useful for making preliminary site evaluations and land-use decisions. This section focuses on the surficial deposits and rock units in the Greater Denver Area, although the properties of these units are similar in the Boulder-Fort Collins-Greeley area and in the Colorado Springs-Castle Rock area (fig. 1). The Greater Denver Area was selected for study because of the diversity of geologic units, availability of geologic and geotechnical data, and rapid rate of urban growth. Much of the information presented in this section was compiled from geologic maps and reports by the U.S. Geological Survey (Bryant and others, 1973; Colton, 1978; Colton and Fitch, 1974; Gardner and others, 1971; Lindvall, 1978, 1979; Maberry, 1972b, 1973; Maberry and Lindvall, 1972, 1974, 1977; Machette, 1977; Machette and others, 1976; Miller and Bryant, 1976; Robinson and Lee, 1974a, 1974b; Robinson and others, 1974; Scott, 1962, 1963a, 1963b, 1972b, 1972d; Scott and others, 1966; Shroba, 1980; Simpson, 1973b, 1973c; Trimble and Fitch, 1974a, 1974b; Trimble and Machette, 1979a, 1979b; Van Horn, 1968, 1972, 1976; and Wells, 1967), county soil surveys by the Soil Conservation

Service (Larsen and Brown, 1971; and Sampson and Baber, 1974), and test data collected by the author. Other sources are cited where appropriate.

Surficial deposits of Quaternary age, including eolian deposits, alluviums, slope deposits, and manmade deposits (fig. 31), cover much of the Colorado Piedmont where they form a variety of landforms, which are major components of the landscape. These deposits are less extensive in the hogback belt and the Front Range (fig. 2) where they are interspersed with large areas of bedrock and are limited mostly to valley bottoms and gentle slopes.

The major factors that influence the physical properties and performance characteristics of the surficial deposits in the Greater Denver Area are grain size[3] (table 4), amount of compaction, and degree of weathering. The first two factors are related mainly to the grain size of the sediments in the source area, distance of transport, and mode and environment of deposition. The degree of weathering tends to increase with the age of the deposit. In general, the Louviers Alluvium and deposits of equivalent age and younger (fig. 31)—which include much of the eolian deposits, flood-plain and terrace alluviums, and slope deposits—are only slightly modified by weathering processes to a depth of about a meter. Most manmade deposits are less than 100 years old and are unweathered. Surficial deposits older than the Louviers Alluvium—which include pediment alluviums, some terrace alluviums, and some slope deposits—however, are more weathered than younger deposits and are characterized by prominent horizons of clay accumulation (Bt horizons) and horizons of carbonate enrichment (Cca and K horizons) that have formed in the upper 1-3 m of these older surficial deposits.

In this section, surficial deposits are grouped, according to mode and environment of deposition, as follows: eolian deposits, flood-plain and terrace alluviums, pediment alluviums, slope deposits, and manmade deposits.

EOLIAN DEPOSITS

GENERAL DESCRIPTION

Loess and eolian sand (fig. 31) are by far the most widespread surficial deposits east of the mountain front. Wind-deposited silt and sand cover extensive areas south and east of the major streams (fig. 1). Much of this material was blown from alluvium exposed along valley floors. Some of the loess, however, was deflated from shallow basins formed in fine-grained sedimentary rocks near the eastern margin of the hogback belt (Scott, 1962; Colton, 1977). Minor amounts of eolian sand were derived from sandstone outcrops and sandy pediment alluviums. Eolian sand is most abundant east of the South Platte River and forms large, generally stable dune fields northeast of Denver. Loess is most widespread west of the South Platte River and to the south and east of the areas mantled by eolian sand. The distribution of eolian deposits, the orientation of sand dunes and deflation basins, and the general southeastward decrease in grain size—especially of eolian sand—all strongly suggest sediment transport by northwesterly winds. Eolian deposits are generally less than 5 m thick and tend to thin in a down-wind direction. In some areas, loess is as much as 7 m thick; locally, large parabolic sand dunes have thicknesses in excess of 15 m.

PHYSICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

Grain-size analyses of eolian material from southeast Denver indicate that most loess is 70-80 percent silt and clay—slightly more silt than clay—20-30 percent sand, and about 1 percent granules; eolian sand is commonly 20-30 percent silt and clay—about twice as much silt as clay—70-80 percent sand, and about 1 percent granules (table 5). Eolian deposits northeast of Denver tend to be slightly more sandy than those in southeast Denver.

Eolian sediments in southeast Denver have a wide range of Atterberg limits. Loess generally has a liquid limit of 40-45 and a plasticity index of about 20, whereas eolian sand has a liquid limit of about 25 and usually is nonplastic. According to the Unified Soil Classification (U.S. Bureau of Reclamation, 1974); (table 6 and fig. 32, this report), most loess is classified as CL and most eolian sand as SM, SP, and SC (table 7).

Eolian materials beneath heavy structures are susceptible to excessive compaction and differential settlement, especially if they are overwatered. Loess that has a dry density of less than 1,400 kg/m^3 (kilograms per cubic meter) and eolian sand that has dry density of less than 1,700 kg/m^3 decrease the most in volume. Test data for eolian sand show a strong inverse relationship between dry density and consolidation; that is, when loaded, the lower the dry density the greater the amount of consolidation. This relationship, however, is not as well defined for loess. Other factors such as the amount and type of clay-size material and the shape and orientation of silt- and clay-size particles may influence the amount of consolidation of loess

[3] In this section, grain-size nomenclature and size classes for grain-size analyses conform to the Wentworth system. In addition, the results of several standard engineering tests are presented in this section. These tests were conducted according to procedures established by the American Society for Testing Materials, which specify grain-size limits that correspond with those of the Unified Soil Classification System.

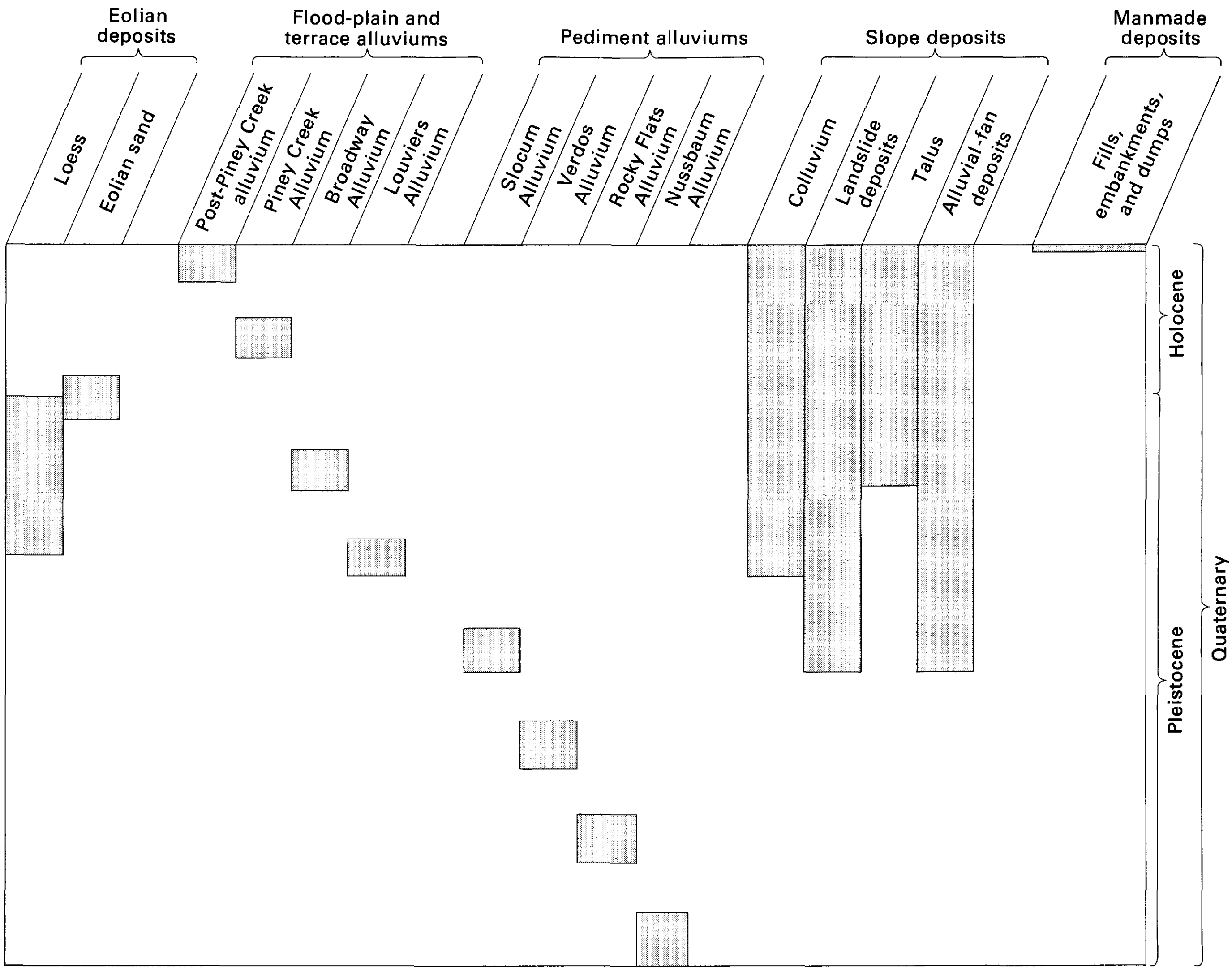

FIGURE 31.—Surficial Quaternary deposits in the Greater Denver Area and their approximate ages. Modified in part from Trimble and Machette (1979b).

under a heavy load. Loess and eolian sand commonly consolidate about 1 percent when wetted and loaded at 25-50 kN/m² (kilonewtons per square meter); however, consolidation of 3-5 percent is not uncommon (table 8).

Eolian sand and sandy loess are nonexpansive when wetted and loaded at 25- 50 kN/m². Some clayey loess, however, expands in excess of 3 percent and exerts swelling pressures of more than 150 kN/m². Average values for loess in southeast Denver are about 1 percent and 25 kN/m², respectively (table 8). The swelling pressure of loess tends to increase as density increases. Clayey Bt horizons, about 10-70 cm thick, in the upper part of the loess tend to have higher swelling potentials than the underlying less clayey loess.

The shear strength of eolian material tends to vary with the grain size and moisture content. Loess in southeast Denver has an unconfined compressive strength of about 100-700 kN/m², and averages about 300 kN/m² (table 8). Eolian sand has much lower values of about 30-45 kN/m² and 35 kN/m², respectively. Test data indicate that a threefold increase in water content of loess can result in as much as a tenfold reduction in unconfined compressive strength. In contrast, measurements for eolian sand show that shear strength decreases with reduced moisture content for samples that range from moist to air dry.

Loess and eolian sand commonly have the following performance characteristics: Excavation is easy with hand tools or light power equipment. Foundation conditions are only fair, owing to considerable frost heaving in the upper meter of the deposit and susceptibility to excessive compaction and differential settlement.

TABLE 4.—*Grain-size scale, showing size classes of the Wentworth and Unified Soil Classification systems*

[Modified from U.S. Bureau of Reclamation (1974) and Schwochow and others (1974). Values in millimeters. . . . . , not specified. Values are boundaries between size classes]

	Clay	Silt	Sand	Gravel			
				Granule	Pebble	Cobble	Boulder
Wentworth system--------	0.0039	0.0625	2	4	64	256	
Unified Soil Classification system--------	.....	[1] .074	[2] 4.76	...	76	305	

[1] Particles less than 0.074 mm in diameter are referred to as silt and clay or fines.
[2] Particles from 4.76 to 76 mm in diameter are referred to as gravel.

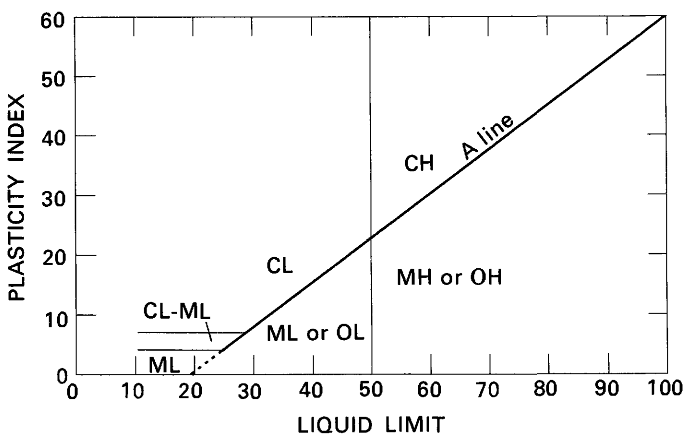

FIGURE 32.—Plasticity chart for the classification of fine-grained materials (50 percent or more by weight smaller than 0.74 mm in diameter) according to the Unified Soil Classification (table 6). Modified from U.S. Bureau of Reclamation (1974, fig. 7). Classification is based on a material's plasticity index versus its liquid limit. The "A" line is an empirical boundary that generally separates inorganic clays of low to high plasticity in the area above the line from inorganic silts and organic silts and clays of low to high plasticity below the line. The vertical line at a liquid limit of 50 separates inorganic silts and organic silts and silty clays of low plasticity and inorganic clays of low to medium plasticity in the area to the left of the line from inorganic silts and clays of high plasticity and organic clays of medium to high plasticity to the right of the line.

Permeability is usually high in eolian sand and moderate in loess. Vertical cuts are unstable and will slump to form slopes of about 10–25°.

FLOOD-PLAIN AND TERRACE ALLUVIUMS

GENERAL DESCRIPTION

The major streams east of the hogback belt (fig. 2) are bordered by extensive flood-plain and terrace deposits that are generally less than 6 m above stream level and are made up of post-Piney Creek alluvium and Piney Creek Alluvium (fig. 31). These alluviums are of Holocene age and are primarily sand to silty sand and sandy silt, respectively. Discontinuous terraces of Broadway and Louviers Alluviums (fig. 31), of late Pleistocene age, are typically 7–20 m above stream level. Broadway Alluvium is most widespread along the east side of the South Platte River, whereas Louviers Alluvium is most extensive along eastward-flowing tributaries. These alluviums are mostly pebbly sands containing minor amounts of pebble to cobble gravel. Locally, they are mantled by eolian deposits that tend to thicken toward the valley margin.

Stream alluviums in the Denver area tend to be thickest along the South Platte River and are progressively thinner along increasingly smaller tributaries. Piney Creek Alluvium and post-Piney Creek alluvium are less than 6 m thick and commonly range from about 1.5 to 4.5 m in thickness. Along major streams these alluviums overlie older gravelly alluvium. Along small intermittent streams post-Piney Creek alluvium is usually less than 1.5 m thick. Broadway Alluvium is commonly about 7.5 m thick and is locally as much as 9 m thick along the South Platte River in downtown Denver. The Louviers Alluvium is one of the thickest surficial deposits in the Denver area. In the valley of the South Platte it is as much as 21 m thick; locally the base of the Louviers is as much as 12 m below present stream level.

The grain size of flood-plain and terrace alluviums east of the mountain front is related to several factors including: (1) nature of the bedrock and surficial deposits in the source area, (2) age of the alluvium, (3) position within the alluvial sequence, (4) stream size or competence, (5) environment of deposition, and (6) distance of transport. Late Pleistocene alluviums along

TABLE 5.—*Grain-size distributions of surficial deposits in the Denver area*

[Values are approximate and are rounded to the nearest 5 percent. <, less than; ≤, less than or equal to; ——5——, range in size of gravel in samples tested]

<table>
<tr><th rowspan="3">Surficial deposit</th><th rowspan="3">Location of samples tested</th><th colspan="6">Grain-size distribution (percent by weight)</th></tr>
<tr><th rowspan="2">Silt and clay</th><th rowspan="2">Sand</th><th colspan="4">Gravel</th></tr>
<tr><th>Granule</th><th>Pebble</th><th>Cobble</th><th>Boulder</th></tr>
<tr><td>Loess</td><td>Southeast Denver</td><td>70-80</td><td>20-30</td><td><5</td><td></td><td></td><td></td></tr>
<tr><td>Eolian sand</td><td>Southeast Denver</td><td>20-30</td><td>70-80</td><td><5</td><td></td><td></td><td></td></tr>
<tr><td>Post-Piney Creek Alluvium.</td><td>Along major streams in the Denver area.</td><td>≤60</td><td>30-90</td><td colspan="3">≤30</td><td></td></tr>
<tr><td>Piney Creek Alluvium.</td><td>Along the South Platte River and Cherry Creek.</td><td>20-70</td><td>30-65</td><td colspan="2">≤15</td><td></td><td></td></tr>
<tr><td>Broadway Alluvium, main body.</td><td>Along the South Platte River.</td><td>0-10</td><td>60-80</td><td colspan="3">10-40</td><td></td></tr>
<tr><td>Broadway Alluvium, fine-grained layers.</td><td>Along the South Platte River.</td><td>40</td><td>55</td><td colspan="3">5</td><td></td></tr>
<tr><td>Louviers Alluvium</td><td>Along major streams in the Denver area.</td><td>0-5</td><td>30-60</td><td colspan="4">35-70</td></tr>
<tr><td>Slocum, Verdos, and Rocky Flats Alluviums, upper parts.</td><td>Between the hogback belt and the South Platte River.</td><td>30-60</td><td>25-45</td><td>≤10</td><td>5-25</td><td></td><td></td></tr>
<tr><td>Slocum, Verdos, and Rocky Flats Alluviums, lower parts.</td><td>Between the hogback belt and the South Platte River.</td><td>10-15</td><td>30-40</td><td>10</td><td>30-40</td><td colspan="2">5-10</td></tr>
<tr><td>Colluvium</td><td>East of the hogback belt.</td><td>60-70</td><td>20-30</td><td colspan="3">10</td><td></td></tr>
</table>

the South Platte River and its major eastward-flowing tributaries consist chiefly of coarse detritus from the crystalline rocks of the Front Range, whereas alluviums of equivalent age along major westward-flowing tributaries are slightly finer grained and were produced by the erosion of sedimentary rocks, mostly sandstone and conglomerate. Younger, valley-bottom alluviums are more locally derived and probably represent the reworking of older surficial deposits. For example, the fine-grained, humic character of the upper part of the Piney Creek Alluvium suggests that this material was eroded from soils formed in silty and clayey surficial deposits, mainly loess and colluvium consisting of loess mixed with disintegrated siltstone and claystone. In addition, (1) late Pleistocene alluviums are more gravelly and less silty than Holocene alluviums; (2) the upper parts of most deposits are finer grained than the lower parts, owing to the deposition of overbank and (or) eolian sediment in the upper parts and the accumulation of minor amounts of pedogenic clay; and (3) alluviums of equivalent age are coarsest in the vicinity of the mountain front and in the central part of the valley of the South Platte River, are slightly finer grained near the valley sides (especially below confluences with minor streams), and are progressively finer grained in increasingly smaller tributary valleys.

PHYSICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

Field observations and test data indicate that alluviums of different ages have different grain-size distributions. The grain size of post-Piney Creek alluvium is highly variable. Along main streams it is a silty sand, sand, or pebbly sand interbedded with pebble gravel and sandy silt. Mainstream post-Piney Creek alluvium is 30-90 percent sand and contains as

TABLE 6.—*Unified Soil Classification*[1] *chart*
[Modified from U.S. Bureau of Reclamation (1974, fig. 7)]

Major categories	Group symbol	Common field description
		Coarse-grained soils[2]
Gravels[3]	GW	Well-graded (engineering sense) gravels and sandy gravels.
	GP	Poorly graded gravels and sandy gravels.
	GM	Silty gravels and poorly graded silty, sandy gravels.
	GC	Clayey gravels and poorly graded clayey, sandy gravels.
Sands[4]	SW	Well-graded sands and gravelly sands.
	SP	Poorly graded sands and gravelly sands.
	SM	Silty sands and poorly graded silty sands.
	SC	Clayey sands and poorly graded clayey sands.
		Fine-grained soils[5]
Slightly plastic[6] silts and clays.	ML	Inorganic silts, very fine sands, and silty or clayey fine sands of low plasticity.
	CL	Inorganic clays and gravell, sandy, or silty clays of low to medium plasticity.
	OL	Organic silts and silty clays of low plasticity.
Highly plastic[7] silts and clays.	MH	Inorganic silts.
	CH	Inorganic clays of high plasticity.
	OH	Organic clays of medium to high plasticity.
		Highly organic soils[8]
	Pt	Peat and other organic-rich sediments.

[1]The Unified Soil Classification is a system that groups unconsolidated materials according to their engineering properties. The first letter of the group symbol indicates grain size and inorganic or organic character of the material. The second letter indicates gradation (engineering sense) and plasticity of the material. Material that is at or near the boundary between two groups is given a dual classification, such as GP-GC.

[2]More than 50 percent by weight is larger than 0.74 mm in diamter.

[3]More than 50 percent by weight of the coarse fraction (greater than 0.74 mm) is larger than 4.76 mm in diamter.

[4]Fifty percent or more by weight of the coarse fraction is 0.74 to 4.76 mm in diameter.

[5]Fifty percent or more by weight is smaller than 0.74 mm in diameter.

[6]Liquid limit is less than 50.

[7]Liquid limit is 50 or more.

[8]Contains abundant fibrous organic matter.

much as 60 percent silt and clay, or as much as 30 percent granule to cobble gravel (table 5). This wide range is probably a result of the erosion of nearby surficial deposits and a relatively short distance of transport.

Piney Creek Alluvium along the South Platte River and its major tributaries consists of two parts that are physically different. The upper part is commonly a humic, slightly calcareous, sandy silt that is interlayered with silty sand and a few lenses of silty clay. The lower part is chiefly sand and some layers of pebble gravel. Grain-size data indicate that Piney Creek Alluvium along the South Platte River and Cherry Creek is made up of 20–70 percent silt and clay, 30–65 percent sand, and 0–15 percent granule to pebble gravel. Piney Creek Alluvium along Cherry Creek is more gravelly and less silty than along the South Platte River. In small tributary valleys that have slopes mantled by loess and fine-grained colluvium, Piney Creek Alluvium is as much as 80 percent silt and clay. In areas of extensive eolian sand, Piney Creek Alluvium is sandy.

Broadway Alluvium along the South Platte is mostly pebbly sand interbedded with sandy silt. At the mountain front it is composed of cobble gravel. Broadway Alluvium along minor streams is sand to sandy silt. Grain-size data show that much of the Broadway Alluvium in the valley of the South Platte River is very sandy and is made up of 0–10 percent silt and clay, 60–80 percent sand, and 10–40 percent granule to cobble gravel. Fine-grained layers average about 40 percent silt and clay, 55 percent sand, and 5 percent granule to pebble gravel.

Louviers Alluvium along major streams is typically a pebbly sand interbedded with pebble to cobble gravel and lenses of silty sand to clayey silt. It is bouldery along perennial streams near the mountain front and is sandy to clayey along intermittent streams. Grain-size analyses for Louviers Alluvium along the South Platte River, Bear Creek, Clear Creek, and Cherry Creek indicate that the alluvium is very gravelly and is composed of 0–5 percent silt and clay, 30–60 percent sand, and 35–70 percent granule to boulder gravel.

Differences in the plasticity of flood-plain and terrace alluviums are in part related to their wide range in grain size. Limited test data indicate that Piney Creek Alluvium has a liquid limit of 30–45 and a plasticity index of 10–25; post-Piney Creek alluvium has slightly lower values (table 7). Most of the Broadway and Louviers Alluviums are nonplastic. Silty layers in the Broadway Alluvium have liquid limits of 20–40 and are nonplastic or have plasticity indices of 20 or less. According to the Unified Soil Classification (U.S. Bureau of Reclamation, 1974), typical group symbols for the above alluviums, in order of decreasing silt and clay and increasing gravel, are: CL, SM, and SC for Piney Creek Alluvium; SC and SW for post-Piney Creek alluvium; SC, SM, and CL for fine-grained layers in Broadway Alluvium; SP and SM for coarse-grained Broadway Alluvium; and SW, GP, and GW for Louviers Alluvium.

Bearing capacities and volume-change characteristics of the stream alluviums depend mostly on grain size and amount of organic matter. Structures built on Piney Creek Alluvium and post-Piney Creek alluvium tend to have more foundation problems than those on older, coarser-grained alluviums. Piney Creek Alluvium along major streams and fine-grained alluviums of various ages along minor streams commonly contain lenses of clayey silt and silty clay. These materials are highly compressible and may cause differential compaction under a light to moderate load.

TABLE 7.—*Atterberg limits and typical Unified Soil Classification group symbols for surficial deposits in the Denver area*

[Values are approximate and are rounded to the nearest 5 percent. NP, nonplastic; ≤, less than or equal to; <, less than; . . . , little or no data]

Surficial deposit	Location of samples tested	Atterberg limits		Unified Soil Classification groupsymbols
		Liquid limit	Plasticity index	
Loess	Southeast Denver	40-45	20	CL
Eolian sand	Southeast Denver	25	NP	SM, SP, SC
Post-Piney Creek alluvium.	Along major streams in the Denver area.	≤40	≤20	SC, SW
Piney Creek Alluvium.	Along the South Platte River and Cherry Creek.	30-45	10-25	CL, SM, SC
Broadway Alluvium, main body.	Along the South Platte River.	...	NP	SP, SM
Broadway Alluvium, fine-grained layers.	Along the South Platte River.	20-40	≤20	SC, SM, CL
Louviers Alluvium	Along major streams in the Denver area.	...	NP	SW, GP, GW
Slocum, Verdos, and Rocky Flats alluviums, upper parts.	Between the hogback belt and the South Platte River.	20-50	10-20	SM, SC, CL
Slocum, Verdos, and Rocky Flats Alluviums, lower parts.	Between the hogback belt and the South Platte River.	15-45	≤20	GP-GC, GC, SM, SC
Colluvium	Southeast Denver	45-50	20-30	CL
Engineered fills and embankments.	Building sites and low-lying areas in the Denver area.	<50	<30	SP, SM, CL

Organic-rich layers in the upper part of the Piney Creek Alluvium are also highly compressible. Some deposits of post-Piney Creek alluvium contain layers of well-sorted sand that may be prone to consolidation. In contrast, much of the Broadway and Louviers Alluviums along major streams are coarse sand and gravel that can support moderately heavy loads and withstand forces of as much as 600 kN/m^2 (table 8). Gravelly, sandy, and most silty alluviums are nonexpansive. However, clayey alluvium, especially Piney Creek Alluvium derived from expansive claystone, commonly shows a few percent increase in volume when wetted and exerts swelling pressures of as much as about 200 kN/m^2 when wetted and loaded at 25-50 kN/m^2 (table 8).

Flood-plain and terrace alluviums commonly have the following performance characteristics: Most alluviums are easily excavated with power equipment. Foundation conditions are generally good in sand and gravel but are poor to very poor in clayey and humic materials. Permeability usually varies from high in sand and gravel to low in clayey alluvium. Vertical cuts are unstable and will slump or ravel to form slopes of about 10-25°.

PEDIMENT ALLUVIUMS

GENERAL DESCRIPTION

East of the hogback belt, the South Platte River and its major eastward-flowing tributaries (fig. 1) are flanked by a series of gently sloping surfaces capped by thin deposits of gravelly pediment alluvium[4] of Pleistocene age. East of the South Platte River, alluvium of similar age is buried beneath widespread eolian deposits. Three and locally four ages of pediment alluvium are recognized in the Greater Denver Area (fig. 31). From youngest to oldest, the three major alluviums and their approximate range in elevation above stream level are Slocum Alluvium (25-35 m), Verdos Alluvium (60-75 m), and Rocky Flats Alluvium (110 m). The Nussbaum Alluvium, the oldest pediment alluvium, is of very limited extent and occurs at elevations of about 15-25 m above the level of the Rocky Flats Alluvium. Slocum Alluvium covers large areas in southwest Denver and locally forms terraces along some of the major eastward-flowing streams.

[4] As used in this section, the term "pediment alluvium" refers to deposits of waterlaid sediment, regardless of thickness, that rest on an erosional, pedimentlike surface cut on the underlying bedrock.

TABLE 8.—*Volume change, swelling pressure, and unconfined compressive strength of surficial deposits in the Denver area*

[Values are approximate; those for volume change are rounded to the nearest 0.5 percent; those for swelling pressure and unconfined compressive strength are rounded to the nearest 5 kN/m² if less than 100 kN/m² or to the nearest 50 kN/m² if greater than 100 kN/m². . . . , little or no data; ≤, less than or equal to; NE, nonexpansive]

Surficial deposit	Location of samples tested	Volume Change: Consolidation[1] (percent)	Volume Change: Swell[2] (percent)	Swelling pressure[3] (kN/m²)	Unconfined compressive strength[4] (kN/m²)
Loess	Southeast Denver	1	1	25	300
Eolian sand	Southeast Denver	1	0	0	35
Piney Creek Alluvium	Along major streams in the Denver area.	...	...	≤200	...
Broadway Alluvium, main body	Along the South Platte River	...	...	NE	≤600
Louviers Alluvium	Along major streams in the Denver area.	...	...	NE	≤600
Slocum, Verdos, and Rocky Flats Alluviums, upper parts.	Between the hogback belt and the South Platte River.	...	...	≤200	...
Slocum, Verdos, and Rocky Flats Alluviums, lower parts.	Between the hogback belt and the South Platte River.	...	...	≤50	...
Colluvium	East of the hogback belt	1	0-4	0-250	...

[1]Percent decrease in volume that occurs when undisturbed material loaded at 25-50 kN/m² is wetted.

[2]Percent increase in volume due to expansion, that occurs after consolidation when material with free access to water is loaded at 25-50 kN/m² for 24 hours.

[3]Additional weight per unit area required to return the expanded material to its original volume.

[4]Maximum axial load required to deform a sample when lateral pressure is equal to atmospheric pressure.

The Verdos and Rocky Flats Alluviums are more common in west Denver and in the area northwest of Denver.

Much of the pediment alluvium is slightly silty, sandy pebble gravel that was deposited by small streams that headed in the hogback belt. These deposits commonly contain layers of clayey to sandy silt and cobble to boulder gravel. Pediment alluvium locally varies from sand and gravel to pebbly silt and clay. Deposits of bouldery cobble gravel are common along the mountain front; most alluviums tend to be coarse grained to the west and fine grained to the east. Terrace alluviums along major streams near the mountain front contain the least amount of silt and clay and the greatest amount of coarse gravel, whereas pediment alluviums of equivalent age, laid down by intermittent streams that head in the sedimentary terrane of the hogback belt, tend to be the most clayey and least gravelly. The upper parts of most deposits are slightly pebbly, sandy silt; this material may be overbank alluvium and (or) old loess.

The fine-grained material in the upper part and the upper part of the underlying gravelly alluvium have been modified to a considerable extent by soil development. Most of these soils have well-developed, clayey Bt horizons that are about 0.5-1 m thick and overlie calcium carbonate-enriched Cca or K horizons that extend to depths of as much as 2-3 m. Many of the granitic and gneissic stones in these soils are disintegrated.

The thickness of pediment alluviums generally averages 3-5 m and commonly ranges from less than 1 to as much as 12 m. Buried stream channels beneath Rocky Flats (fig. 1), however, contain alluvial fills as much as 37 m thick (Hurr, 1976). Pediment deposits tend to thin from the hogback belt eastward toward the South Platte River.

PHYSICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

Analyses of the pediment alluviums show that they have similar grain-size distributions. The lower parts typically are 10-15 percent silt and clay, 30-40 percent sand, 10 percent granules, 30-40 percent pebbles, and 5-10 percent cobbles and boulders (table 5). This material is commonly interbedded with clayey layers made up of 50 percent or more silt and clay, and gravelly alluvium that contains 20-35 percent cobbles and boulders. Locally, much of the lower parts of the alluviums range from clayey material composed of as much as 60 percent silt and clay to bouldery material containing as much as 40 percent cobbles and boulders. The upper 1-1.5 m of pediment deposits contain 30-60 percent silt and clay, 25-45 percent sand, 10 percent or less granules, and 5-25 percent pebbles. Weathering causes some of this three- to fourfold increase in silt and clay and the marked decrease in gravel in the upper part of the alluvium, relative to the alluvium at a depth of 2-3 m.

Pediment alluviums have a considerable range in plasticity, owing primarily to the wide variation in grain size. Test data indicate that the lower parts of Slocum, Verdos, and Rocky Flats Alluviums commonly have liquid limits of 15-45 and are nonplastic or have plasticity indices of 20 or less (table 7). The fine-grained upper parts have slightly higher values that frequently range from 20-50 for the liquid limit and 10-20 for the plasticity index. Liquid limits of as much as 60 and plasticity indices as high as 30 have been measured for material from the upper 1-1.5 m and for material from fine-grained layers in the lower parts of the alluviums. The upper parts of the pediment alluviums are usually classified, according to the Unified Soils Classification (U.S. Bureau of Reclamation, 1974), as SM, SC, and CL, whereas the lower parts are more variable and are commonly designated as GP-GC, GC, SM, and SC.

Pediment alluviums have different bearing strengths, depending on the relative abundance of clay and gravel. The upper parts and fine-grained layers in the lower parts probably have bearing capacities slightly greater than those of loess. Coarse-grained layers in the lower parts can support greater loads than can the fine-grained upper parts and probably have bearing capacities equal to or slightly greater than those of Broadway and Louviers Alluviums.

The swelling potential of pediment alluviums varies with the amount of clay and tends to decrease with depth. Clayey Bt horizons in the fine-grained upper parts generally produce the highest swelling pressures. Very clayey Bt horizons may exert swelling pressures of as much as 200 kN/m^2, whereas moderately clayey Bt horizons probably have swelling pressures of less than 50 kN/m^2 (table 8). The underlying horizon of carbonate enrichment is less expansive than the Bt horizon, owing to the abundance of nonexpansive calcium carbonate, lower clay content, and the stabilizing effect of calcium ions on the montmorillonitic clays. The upper 2–3 m of pediment alluviums contain as much as 40–95 percent calcium carbonate in the less than 2-mm fraction (Machette and others, 1976). Because the lower parts of pediment alluviums tend to be more sandy and gravelly than the upper parts, they probably have swelling pressures of less than 50 kN/m^2.

Pediment alluviums commonly have the following performance characteristics: Excavation is easy to moderately easy with light power equipment; however, scattered large boulders within a few kilometers of the hogback belt, and indurated K horizons cemented by calcium carbonate, may require the use of heavy power equipment. Foundation conditions are generally good in the sandy and gravelly lower parts of the alluviums but are poor in layers of clayey alluvium and clayey Bt horizons, owing to moderate swelling pressures and lower bearing capacities. Permeability is usually high in sand and gravel but commonly is low in clayey silt and in carbonate-cemented horizons. Vertical cuts are unstable and will slump or ravel to form slopes of about 15–25°.

SLOPE DEPOSITS

GENERAL DESCRIPTION

Slopes in the Greater Denver Area are mantled by thin surficial deposits that have moved under the influence of gravity or running water. These deposits include colluvium (mostly slope wash and sheetwash), landslide deposits, talus, and alluvial-fan deposits (fig. 31). Colluvium is widespread on slopes steeper than 2°. Most landslides are on steep slopes near the mountain front. Landslides on sedimentary rocks are usually on slopes steeper than 8°, whereas those on crystalline rocks are on slopes steeper than 15°. Landslide deposits are most common along the flanks of steep-sided landforms, such as Rocky Flats, Green Mountain, and North and South Table Mountains (fig. 1), all of which are made up primarily of fine-grained sedimentary rocks of low shear strength capped by gravel or lava flows. Landslide deposits are present but less common on the east-facing slope of the hogback of the Dakota Group, dipslopes on the Fountain Formation and Lyons Sandstone, steep canyon sides, and on crystalline rocks along the mountain front. Talus is limited to canyon sides steeper than 15°. Alluvial-fan deposits accumulate mostly along minor streams where a decrease of gradient diminishes transport capacity. Near the mountain front, alluvial-fan deposits are on slopes of about 10–20°. Farther east, along the margins of flood plains of major streams, they are on slopes of about 3–5°.

Slope deposits tend to reflect the grain size of the surficial deposits and rock units from which they are derived farther upslope. They rarely are more than a few meters thick. On the piedmont, colluvium is chiefly pebbly, sandy, silt and clay derived from loess, pediment alluvium, and fine-grained sedimentary rocks. Along the eastern margin of the Front Range and in the hogback belt, however, colluvium commonly is cobbly to bouldery and contains angular rock fragments as much as a meter across. Limited grain-size data indicate that colluvium east of the hogback belt is made up of about 60–70 percent silt and clay, 20–30 percent sand, less than 10 percent granules and pebbles and, locally, a small amount of cobbles (table 5). Most colluvium is less than 3 m thick and commonly less than 1.5 m.

Landslide deposits are composed of locally derived material. Some have moved in historic time, and some are still moving. Depending on the source, landslide deposits range in composition from bouldery debris in a fine-grained matrix to silty and clayey material with a few scattered stones. Most landslide deposits are less than 6 m thick.

Talus consists mostly of angular, bouldery rubble that has fallen or rolled down slopes underlain by crystalline rocks. Loose, unstable talus has large voids and a sparse lichen cover on surface boulders, whereas stable talus generally has a matrix of sand or sandy silt and a nearly continuous lichen cover on surface boulders. Talus is commonly less than 6 m thick.

Alluvial-fan deposits are heterogeneous masses of waterlaid material that are characterized by sharp lateral and vertical changes in grain size. Deposits commonly range from bouldery sand and gravel along the mountain front to sand, sandy silt, and silty clay along the margins of flood plains east of the hogback belt. Most alluvial-fan deposits are less than 4.5 m thick.

Most slope deposits are of Holocene or latest Pleistocene age and, therefore, are only slightly modified by soil development. The upper meter of many of these deposits shows little evidence of stone weathering and only minor accumulation of clay or calcium carbonate.

PHYSICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

Atterberg limits for slope deposits are similar to those of the original surficial deposits and rock units prior to downslope movement. Limited data suggest that fine-grained colluvium in southeast Denver, derived from loess and the Denver Formation, has liquid limits of 45–50 and plasticity indices of 20–30 (table 7). This material is usually classified as CL, according to the Unified Soil Classification (U.S. Bureau of Reclamation, 1974).

The volume-change characteristics and bearing capacity of colluvium are related to those of the source materials. Fine-grained colluvium undergoes moderate volume change when loaded and wetted. Structures founded on this material may be susceptible to damage owing to differential compaction under heavy loads and uneven heaving under light loads. When wetted and loaded at 25–50 kN/m², fine-grained colluvium decreases about 1 percent in volume, and then increases 0–4 percent (table 8), depending on the original bulk density, moisture content, and amount and type of clay. Swelling pressures produced by colluvium are highly variable and differ with the composition of the source material. Values commonly range from zero for sandy material to about 250 kN/m² for colluvium derived from expansive rock units. Values for percent swell and swelling pressure of fine-grained colluvium in southeast Denver average about 1.5 percent and 60 kN/m², respectively. In the Pueblo area, colluvium and other surficial deposits have swelling pressures that are about one-half those of the source material (Scott, 1969). Colluvium usually has a lower bearing capacity than that of the source material prior to downslope movement. Colluvium and other materials on steep slopes may fail by landsliding if overloaded or saturated, or if lateral support is removed.

The bearing capacity and volume-change characteristics of landslide deposits, talus, and alluvial-fan deposits are not well known, but they must range widely depending on the grain size of the transported material as well as the type of deposit and distance of transport. Landslide deposits derived from fine-grained materials tend to have lower bearing capacities than those of the original, undisturbed material and have similar or slightly lower swelling pressures. The ability of talus to support loads depends on steepness of slope, size of debris, angularity, amount of block-to-block contact, and amount and type of interstitial material. Because of the very small amount of interstitial clay, talus is nonexpansive. The bearing capacity and shrink-swell characteristics of alluvial-fan deposits change with the grain size of the sediment; gravelly alluvial fans probably are comparable to pediment alluviums, whereas alluvial fans derived from eolian sediments would probably have values similar to those of their eolian sources.

Slope deposits commonly have the following performance characteristics: Excavation is generally easy with power equipment, except for those deposits near the mountain front that contain large boulders. Foundation conditions are commonly very poor to fair for landslide deposits, poor for talus, poor to fair for colluvium and silty alluvial-fan deposits, and good for sandy and gravelly alluvial-fan deposits. Silty and clayey slope deposits are prone to excessive expansion and contraction, differential compaction, and frost heaving. Permeability is usually high in talus and sandy and gravelly alluvial-fan deposits and generally is low in silty alluvial-fan deposits and landslide deposits and colluvium derived from fine-grained materials. Slope stability is generally poor, owing to landslide potential, except on alluvial fans with low surface gradients.

MANMADE DEPOSITS

GENERAL DESCRIPTION

Manmade deposits are common features in the urban environment and include engineered fills, sanitary landfills, highway and railroad embankments, earth dams, trash dumps, and spoil piles (fig. 31). These deposits and man-modified land regraded for residential, commercial, and industrial development cover many tens of square kilometers of the Greater Denver Area. Artificial fills are especially common around buildings and along segments of roads and railroads in low-lying areas, in reclaimed gravel pits, and along irrigation ditches.

Manmade deposits are composed of varying amounts of surficial material and refuse, and they differ significantly in degree of compaction. They range in thickness from less than 1 m to as much as 45 m. Embankments and engineered fills are unmodified by weathering processes, whereas most landfills and dumps are in various stages of decomposition.

Engineered fills and embankments vary widely in composition but consist primarily of poorly sorted but well-compacted mixtures of silt, sand, and pebbles that contain minor amounts of cobbles and clay. Landfills are made up mostly of poorly compacted industrial and residential wastes interlayered with surficial material. Dump fills and soil piles typically consist of uncompacted or very poorly compacted surficial material, demolition debris, and other poorly sorted materials that are interspersed with large voids.

PHYSICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

Most engineered fills and embankments have plasticity and volume-change characteristics that are similar to those of the original surficial materials from which they were derived. They usually have low liquid limits and plasticity indices, generally less than 50 and less than 30 respectively (table 7), and they are nonexpansive. Engineered fills and embankments are commonly classified as SP, SM, or CL, according to the Unified Soil Classification (U.S. Bureau of Reclamation, 1974). The physical properties and Unified Soil Classification of nonengineered fills are highly variable and depend primarily on the type and amount of surficial material that was placed in the fill.

Manmade deposits commonly have the following performance characteristics: Excavation with power equipment is easy in embankments, earth dams, and engineered fills and is easy to difficult in landfills, trash dumps, and spoil piles. Foundation conditions are very poor to poor on landfills, trash dumps, and spoil piles and are generally good for light structures on engineered fills. Uncompacted fills settle unevenly and compact slowly or rapidly with time. Permeability is highly variable and is probably high in trash dumps, moderate to high in other uncompacted fills, and low in engineered fills. When placed in excavations in permeable material, dump fills and landfills are potential sources of ground water pollution. In addition, unvented landfills are sources of methane and other potentially hazardous gases that are produced by the microbial decomposition of organic materials. Slope stability is poor for uncompacted fills and generally good for engineered fills.

SEDIMENTARY ROCK UNITS

Sedimentary rocks—mainly claystone, siltstone, shale, and sandstone, and lesser amounts of conglomerate and limestone—make up most of the bedrock east of the Front Range (table 1). Other sedimentary units include minor beds of gypsum and gypsiferous siltstone in the hogback belt south of Morrison, thin seams of subbituminous coal along the eastern margin of the hogbacks, and thick lignite deposits east of Denver (fig. 1). Sediments in the piedmont differ from those in the hogback belt in that the former tend to be more expansive and less well indurated.

To a large extent, the physical properties and performance characteristics of the sedimentary rocks in the Greater Denver Area are related to: (1) grain size, (2) mineralogy of the clay-size particles, (3) degree of lithification, including the amount of compaction and cementation, (4) amount and type of any water-soluble minerals, and (5) relative abundance and orientation of fractures and bedding planes. Much of the sedimentary rock at or near the surface is only slightly weathered. The limited extent and shallow depth of weathering (a few meters or less) is probably due in part to the degree of lithification and low content of relatively unstable minerals. Weathering generally results in a reduction in density and bearing capacity, owing to the removal of unstable minerals and (or) an increase in the amount of voids or fractures. Weathering also tends to increase the swelling pressures of clayey rocks.

In this section, sedimentary rock units are grouped, according to potential volume change and degree of induration, into the following categories: (1) slightly to highly expansive and weakly indurated units, (2) moderately to highly expansive and weakly indurated units, (3) nonexpansive and weakly to moderately indurated units, (4) nonexpansive and nonindurated units, and (5) nonexpansive to slightly expansive and moderately to strongly indurated units.

SLIGHTLY TO HIGHLY EXPANSIVE AND WEAKLY INDURATED UNITS

GENERAL DESCRIPTION

The Graneros Shale, Greenhorn Limestone, Carlile Shale, Smoky Hill Shale Member of the Niobrara Formation (table 1), and the lower and upper shale units and the transition unit of the Pierre Shale (table 1; fig. 33) are made up primarily of fine-grained, shaly rocks that are slightly to highly expansive and weakly indurated. These rock units are exposed in a narrow zone along the western margin of the piedmont just east of the hogbacks (fig. 2).

The rock units consist mainly of noncalcareous to very calcareous, overconsolidated, silty claystone and very clayey to sandy siltstone and shale. All of the rock units, except the lower shale unit of the Pierre, contain a small amount of clayey to silty sandstone. Several thin beds of dense limestone are present in the upper part of the Greenhorn Limestone; chalky limestone occurs near the top and in the lower one-half of

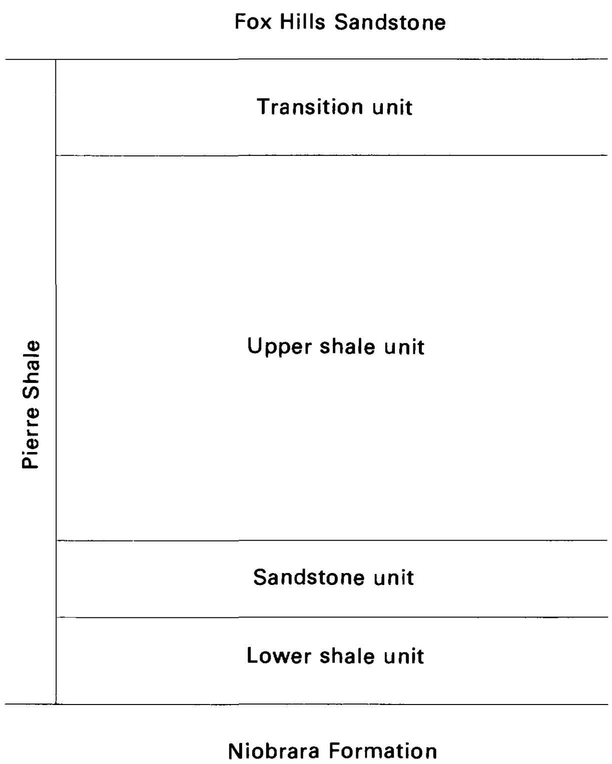

Figure 33.—Generalized lithologic subdivisions of the Pierre Shale west of Denver. Modified from Van Horn (1976).

the Smoky Hill. Individual beds are several centimeters to about 10 m thick and are laterally persistent. Layers of highly expansive bentonite about 0.5–30 cm thick are present locally. Zones of hard limestone and ironstone concretions, as much as a half meter in diameter, are common in the Pierre. Most sandstones and siltstones are cemented by clay, and locally by calcium carbonate and iron oxide. Calcium montmorillonite and mixed-layer illite-montmorillonite are the chief clay minerals in the transition unit of the Pierre; the other rock units contain mixed-layer illite-montmorillonite, montmorillonite, illite, kaolinite, and a minor amount of chlorite. Silt and sand grains are mostly quartz, feldspar, and calcite. (For additional information, see the lithologic descriptions in the section on "Descriptive outline of rock units").

PHYSICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

Few data are available for the grain-size distributions, Atterberg limits, and Unified Soil Classification group symbols for the various fine-grained rock types in the above units. One grain-size analysis for siltstone of the Graneros and one for shale of the Smoky Hill indicate that these rocks are composed of clay- and silt-size particles. The siltstone is 55 percent clay and 45 percent silt, whereas the shale is 70 percent clay, 25 percent silt, and 5 percent sand (table 9). Both have a liquid limit of 30 and a plasticity index of 10. Their Unified Soil Classification group symbol (U.S. Bureau of Reclamation, 1974) is CL (table 10). As opposed to the small amount of data available for the Greater Denver Area, a considerable amount of test data has been summarized for clayey rocks of Late Cretaceous age in the Pueblo area (fig. 1, this report; Scott, 1969). Near Pueblo, shales of the Graneros, Greenhorn, and Carlile are about 60-65 percent clay, 35 percent silt, and 0–5 percent sand. Shales of the Niobrara are slightly less clayey and are about 55 percent clay and 45 percent silt. Shales of the Pierre consist of about 60 percent clay and 40 percent silt. The Atterberg limits for the above shales are related primarily to their grain-size distributions. Both the liquid limit and plasticity index tend to increase as the clay content increases. Shales of the Graneros, Greenhorn, and Carlile have liquid limits of about 35–45 and plasticity indices of 10–15. Shales of the Niobrara have lower values owing to their slightly lower clay content. The liquid limits and plasticity indices of these sediments are about 30–35 and 5–10, respectively. Values for the shales of the Pierre are more variable than those for the above units. They range from about 30–55 for the liquid limits and 10–25 for the plasticity indices. Shales of the Graneros, Greenhorn, Carlile, and Smoky Hill are usually classified as ML, according to the Unified Soil Classification (U.S. Bureau of Reclamation, 1974), whereas similar rock types of the Pierre are commonly classified as CL, ML, and CH (Scott, 1969).

The various rock units and the different rock types within these units have a wide range in swelling pressures and bearing capacities. Swelling pressures for the fine-grained rock types commonly range from less than about 75 kN/m^2 for the upper two-thirds of the lower shale unit of the Pierre to about 75–350 kN/m^2 for the lower one-third of the lower shale unit of the Pierre and the other rock units. Some of the Graneros, however, is very expansive; bentonite at the top of the formation and siliceous shale at the base have swelling pressures of 520 and 560 kN/m^2, respectively (table 11). Sandstone and dense limestone have higher bearing capacities than claystone, siltstone, shale, or chalky limestone.

Slightly to highly expansive and weakly indurated sedimentary units commonly have the following performance characteristics: Weathered and unweathered rock are usually easily excavated with power equipment. Foundation conditions are generally poor on siltstone and claystone, owing primarily to high swelling pressures and large volume change. Beds of dense limestone and thick sandstone beds provide more suit-

TABLE 9.—*Grain-size distributions of weakly to stongly indurated sedimentary rock units and weathered igneous and metamorphic rock units in the Greater Denver Area*

[Values are approximate and area rounded to the nearest 5 percent. ——5——, range in size of gravel in samples tested; <, less than; . . . , little or no data]

Rock units	Grain-size distribution (percent by weight)					
	Silt and Clay	Sand	Gravel			
			Granule	Pebble	Cobble	Boulder
Siltstone of the Graneros Shale	100	0				
Smoky Hill Shale, Member of the Niobrara Formation	95	5	0			
Fox Hills Sandstone	20-40	60-80	0			
Sandstone of the Laramie Formation	10-20	80-90	0			
Sandstone of the Arapahoe Formation	10-35	65-80	0-10	0-5	0	
Claystone of the Denver Formation	85-95	5-15	0			
Siltstone of the Denver Formation	70	30	0			
Sandstone of the Denver Formation	20	75	5			
Claystone of the Dawson Arkose	75	25	0			
Sandstone of the Dawson Arkose	20-35	65	0-15			
Castle Rock Conglomerate	<15	35-50	40-70			
Lyons Sandstone	5-20	80-95	0			
Sandstone of the Lytle Formation	5	95	0			
Sandstone of the South Platte Formation	25	75	0			
Siltstone of the Lykins Formation	100	0				
Siltstone of the Morrison Formation	90	10	0			
Claystone of the Laramie Formation	100	0				
Weathered gneiss and schist[1]	10	40	15	35	. .	. .
Weathered granitic rocks[1]	5	35	25	35	. .	. .

[1] Grain-size data for decomposed and naturally disaggregated material less than 64 mm in diameter.

able foundation conditions. Permeability commonly ranges from negligible in claystone and siltstone to low to moderate in fractured sandstone and limestone. Trafficability on clayey rock is generally poor. Undisturbed slopes and revegetated cuts, less than several meters in height, on gentle slopes tend to be stable, whereas unvegetated slopes are prone to gullying and deflation, and steep, unvegetated cuts greater than several meters in height may fail.

MODERATELY TO HIGHLY EXPANSIVE AND WEAKLY INDURATED UNITS

GENERAL DESCRIPTION

The sandstone unit of the Pierre Shale (fig. 33), the Fox Hills Sandstone, the Laramie, Arapahoe, and Denver Formations, the Dawson Arkose, and the Green Mountain Conglomerate (table 1) are made up of varying amounts of fine-grained to very coarse grained sediments that are moderately to highly expansive and weakly indurated. These rock units occur in the piedmont, along the eastern margin of the hogback belt (fig. 2).

The sandstone unit of the Pierre and the Fox Hills, Laramie, Arapahoe, and Denver consist mostly of interbedded silty to sandy claystone, clayey to sandy siltstone, and silty to pebbly sandstone. Conglomerate is generally absent from the Laramie and older rock units, but it makes up a minor amount of the Arapahoe and Denver. Thin coal beds are locally present in the Denver (Landis, 1959) and in the lower 60 m of the Laramie (Van Horn, 1976). In areas away from the mountain front, the Denver contains thick lignite beds (Soister, 1974). In comparison, the Dawson and Green Mountain are composed primarily of conglomerate and conglomeratic sandstone and lesser amounts of micaceous sandstone and sandy siltstone and claystone. Conglomerate is most abundant in the lower half of the Dawson and in the lower and upper one-third of the Green Mountain. Pebble- to cobble-size clasts are common, and boulders longer than a meter are locally present. Beds of sandy ironstone, less than a half meter thick, occur in the upper part of the Dawson (Scott and Varnes, 1967).

The thickness and lateral continuity of individual beds differ among the various formations. Individual beds in the Laramie and Fox Hills are several centimeters to a few tens of meters thick and are laterally persistent, whereas beds in the younger rock units are a few centimeters to several tens of meters thick, tend to be lenticular, and pinch out within a few meters to less than a kilometer. Zones containing iron- or car-

TABLE 10.—*Atterberg limits and typical Unified Soil Classification group symbols for weakly to moderately indurated sedimentary rock units and weathered igneous and metamorphic rock units in the Greater Denver Area*

[Values are approximate and are rounded to the nearest 5 percent. <, less than; . . . , little or no data; NP, nonplastic; P, slightly plastic]

Rock units	Atterberg limits: Liquid limit	Atterberg limits: Plasticity index	Unified Soil Classification group symbols
Siltstone of the Graneros Shale-----	30	10	CL
Smoky Hill Shale Member of the------ Niobrara Formation.	30	10	CL
Claystone of the Denver Formation---	50-80	30-50	CH
Siltstone of the Denver Formation---	35-55	15-30	CL
Sandstone of the Denver Formation---	35	<10	SM
Claystone of the Dawson Arkose------	40-65	10-25	MH
Siltstone of the Dawson Arkose------	...	...	ML
Sandstone of the Dawson Arkose------	20-50	<20	SC
Conglomerate and Sandstone of the--- Castle Rock Conglomerate.	...	NP-P	GP,GW,SP,SW
Siltstone of the Lykins Formation---	25	<5	ML
Siltstone of the Morrison Formation-	25	5	ML
Claystone of the Laramie Formation--	55	20	MH
Weathered gneiss and schist[1]--------	20-30	NP	GW
Weathered granitic rocks[1]-----------	20-30	NP	GW

[1] Atterberg limits and Unified Soil Classification for decomposed and naturally disaggregated material.

TABLE 11.—*Swelling pressure and unconfined compressive strength of nonexpansive to highly expansive and weakly to strongly indurated sedimentary rock units in the Greater Denver Area*

[Values are approximate and are rounded to the nearest 5 kN/m² for swelling pressure and to the nearest 50 kN/m² for unconfined compressive strength. <, less than; . . . , little or no data; NE, nonexpansive]

Rock units	Swelling pressure (kN/m²)	Unconfined compressive strength (kN/m²)
Claystone and siltstone of the upper two-thirds of the lower shale unit of the Pierre Shale----------------------------------	75	...
Claystone and siltstone of the Graneros Shale, Greenhorn Limestone, Carlile Shale, Smoky Hill Shale Member of the Niobara Formation, lower one-third of the lower shale unit, upper shale unit, and transition unit of the Pierre Shale------	75-350	...
Bentonite of the Graneros Shale----------------	520	...
Siliceous shale at base of the Graneros Shale Claystone of the sandstone unit of the Pierre Shale---	560	...
Claystone of the Fox Hills Sandstone and the Laramie Formation-----------------------------	60-295	...
Claystone of the Arapahoe Formation------------	15-345	...
Claystone of the Dawson Arkose-----------------	130-360	...
Sandstone of the Dawson Arkose-----------------	...	200-400
Claystone of the Denver Formation--------------	140-930	250-1,000
Siltstone of the Denver Formation--------------	<120	500-1,000
Sandstone of the Denver Formation--------------	<50	<350
Conglomerate and sandstone of the Castle Rock Conglomerate-----------------------------	NE	...
Claystone the Ralston Creek, Morrison, Lytle, and South Platte Formations------------------	<75	...
Siltstone of the Lykins Formation--------------	30	...
Siltstone of the Morrison Formation------------	40	...

bonate-cemented concretions, as much as 30 cm in diameter, are locally present in sandy beds in the Laramie, Fox Hills, and Arapahoe.

The degree of induration of the coarse-grained rocks varies somewhat and is related to the type of interstitial material. Most sandstone and conglomerate are weakly indurated and loosely bonded by clay or calcium carbonate; more strongly indurated rocks are cemented by iron oxide and silica. The clay-size fraction of the claystones is composed primarily of montmorillonite, mixed-layer illite-montmorillonite, and (or) kaolinite. Montmorillonite is the chief clay mineral in the Denver, whereas illite and montmorillonite or mixed-layer illite-montmorillonite are common in the Arapahoe and the sandstone unit of the Pierre. Kaolinite and montmorillonite or mixed-layer illite-montmorillonite are the principle clay minerals in the Laramie, Fox Hills, and Dawson. (For additional information, see the lithologic descriptions in the section on "Descriptive outline of rock units."

PHYSICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

Few test data are available for the different lithologies of the Fox Hills, Laramie, and Arapahoe. Limited grain-size data suggest that sandstone of the Fox Hills contains more silt and clay than sandstone of the Laramie, and that sandstone of the Arapahoe has a greater range in composition than sandstone of the Fox Hills or the Laramie. The grain-size distribution for sandstone of the Fox Hills is about 20-40 percent silt and clay and 60-80 percent sand; for sandstone of the Laramie about 10-20 percent silt and clay and 80-90 percent sand; and for sandstone of the Arapahoe about 10-35 percent silt and clay, 65-80 percent sand, 0-10 percent granules, and 0-5 percent pebbles (table 9, this report; McConaghy and others, 1964).

Grain-size data for equivalent lithologies of the Denver and Dawson indicate that they differ slightly in grain-size distribution. Claystone of the Denver is commonly composed of 85-95 percent silt and clay and 5-15 percent sand, whereas the same rock type in the Dawson is slightly more sandy and averages about 75 percent silt and clay and 25 percent sand (table 9). Generally, clay-size particles are slightly more abundant than silt-size particles. In the Denver, siltstone is more sandy than claystone and consists of about 70 percent silt and clay and 30 percent sand. Sandstone of the Denver averages about 20 percent silt and clay, 75 percent sand, and 5 percent granule to pebble gravel; sandstone of the Dawson is slightly finer grained and is composed of about 20-35 percent silt and clay, 65 percent sand, and 0-15 percent granule to pebble gravel.

The plasticity characteristics of the various rock types of the Denver and Dawson are related chiefly to the relative abundance of silt- and clay-size particles. Liquid limits and plasticity indices for the Denver commonly range from about 50-80 and 30-50 respectively for claystone, 35-55 and 15-30 for siltstone, and 35 and less than 10 for sandstone (table 10). In comparison, claystone of the Dawson usually has a liquid limit of 40-65 and a plasticity index of 10-25, whereas sandstone has a liquid limit of 20-50 and a plasticity index of less than 20. Claystone, siltstone, and sandstone of the Denver are usually classified as CH, CL, and SM, respectively, according to the Unified Soil Classification (U.S. Bureau of Reclamation, 1974); equivalent rock types of the Dawson are commonly designated as MH, ML, and SC.

Values for swelling pressure, percent swell, and bearing capacity correlate with rock type, although values for individual rock types vary for different formations. For example, swelling pressures for claystone commonly range from about 60 kN/m^2 for the sandstone unit of the Pierre, to 60-295 for the Fox Hills and Laramie, 15-345 for the Arapahoe, and 130-360 kN/m^2 for the Dawson, to as much as 140-930 kN/m^2 for the Denver (table 11). Siltstone and sandstone of the Denver have swelling pressures that are about one-fifth and one-twentieth, respectively, that of claystone of the same formation. Sandstone of the Dawson is more clayey and more expansive then the sandstone of the Denver. Sandstone of the Dawson commonly exerts expansive forces of about one-half to one-third those of the sandy claystone of the Dawson. Percent swell for sediments of the Denver, under loads of 25-50 kN/m^2, corresponds with swelling pressure and averages about 0.5 percent for sandstone, 1 percent for siltstone, and 4 percent for claystone. Values of as much as 10 percent, for percent swell, have been reported for claystone of the Denver. Test results indicate that claystone and siltstone of the Denver commonly have unconfined compressive strengths of about 250-1,000 kN/m^2 (table 11). Sandstone and weathered siltstone and claystone of the Denver have values of about one-half to one-fifth as much. Arkosic sandstone of the Dawson has an unconfined compressive strength of about 200-400 kN/m^2, which is generally higher than that of sandstone of the Denver.

The performance characteristics of moderately to highly expansive and weakly indurated sedimentary units differ considerably with rock type. Most claystone and siltstone are easy to excavate with power equipment. These rock types tend to have poor foundation conditions and trafficability, low to very low permeability, high susceptibility to frost heave and erosion, and relatively unstable natural and manmade slopes. In contrast, most sandstone and conglomerate are moderately difficult to excavate with power equipment. They generally have good foundation conditions and trafficability, low to moderate permeability, low susceptibility to frost heave and erosion, and relatively stable natural and manmade slopes. Locally, the Denver and Arapahoe contain sulfates and other salts which are deleterious to certain kinds of cement and may cause corrosion of unprotected steel pipes.

NONEXPANSIVE AND WEAKLY TO MODERATELY INDURATED UNITS

GENERAL DESCRIPTION

The Castle Rock Conglomerate (table 1) consists mostly of weakly to moderately cemented conglomerate and sandstone that are nonexpansive. The Castle Rock underlies part of the large interstream area east of the hogback belt between Denver and Colorado Springs (fig. 1). The lower part of the Castle Rock is a very coarse conglomerate interbedded with arkosic sandstone. Some of the clasts are as much as a meter in diameter. The upper part is coarse arkosic sandstone interstratified with thin beds of pebble conglomerate (Romero, 1976). Siltstone and claystone are present in the eastern part of the outcrop area. Individual beds are lenticular and vary in thickness over short distances. Much of the formation is weakly to moderately cemented by iron oxide, clay, and locally by calcium carbonate; parts of it are well indurated and cemented by iron oxide and minor amounts of silica. Conglomerate consists chiefly of rock fragments, quartz, and feldspar, whereas sandstone is made up mostly of quartz, feldspar, and some mica. (For additional information, see the lithologic description in the section on "Descriptive outline of rock units.")

PHYSICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

The physical properties of the Castle Rock are strongly influenced by the low content of silt and clay and the degree of lithification. Limited test data indicate that the conglomerate is less than 15 percent silt and clay, 30-50 percent sand, and about 40-70 percent granule to boulder gravel (table 9). The matrix is fine grained and is nonplastic to slightly plastic (table 10). Much of the formation would probably be classified, according to the Unified Soil Classification (U.S. Bureau of Reclamation, 1974), as poorly to well-graded sand and gravel (GP, GW, SP, and SW). Sandstone and conglomerate of the Castle Rock are nonexpansive (table 11) and probably have bearing capacities that are greater than or equal to those of the arkosic sandstone and conglomerate of the Dawson.

The Castle Rock commonly has the following performance characteristics: The conglomerate and most of the sandstone are moderately difficult to difficult to excavate with power equipment and may require blasting. Both rock types have good foundation conditions and trafficability because of the adequate bearing capacity and low clay content. Permeability usually ranges from low in the unfractured rock to moderate to high along fractures. The formation has low susceptibility to frost heave and erosion. It generally forms stable natural and manmade slopes; however, rockfalls and debris slides may form locally where the formation caps steep-sided mesas.

NONEXPANSIVE AND NONINDURATED UNITS

GENERAL DESCRIPTION

High-level gravel deposits, of Pliocene to Oligocene age, cap some of the ridges and spurs west of the mountain front, along Clear Creek and near the communities of Evergreen and Pine (fig. 1). These deposits are about 300 m above stream level. They are composed of rounded to subangular pebbles, cobbles, and boulders as much as 6 m in diameter in a sandy matrix (Bryant, 1974; Peterson, 1964; Sheridan and others, 1972). The major rock types are granite, gneiss, quartz, quartzite, migmatite, and porphyry. The thickness of these deposits has not been determined, although those in the vicinity of Pine are estimated to be about 8–30 m thick (Peterson, 1964).

PHYSICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

The physical properties and performance characteristics of high-level gravel deposits are not known. They may be somewhat similar to those of bouldery pediment alluvium along the eastern margin of the hogback belt.

NONEXPANSIVE TO SLIGHTLY EXPANSIVE AND MODERATELY TO STRONGLY INDURATED UNITS

GENERAL DESCRIPTION

The Fountain Formation, Lyons Sandstone, the Lykins, Ralston Creek, and Morrison Formations, the Lytle and South Platte Formations of the Dakota Group, and the Fort Hays Limestone Member of the Niobrara Formation (table 1) are made up of varying amounts of sandstone and conglomerate or limestone, and fine-grained shaly rocks that are nonexpansive to slightly expansive and moderately to strongly indurated. These rock units are exposed in the hogback belt (fig. 2) and along its eastern flank.

The Fountain is composed of conglomeratic sandstone, conglomerate, and some micaceous siltstone and fine-grained sandstone. The Lyons is mostly fine- to medium-grained sandstone, and some conglomerate and siltstone. The Lykins is predominantly calcareous, clayey to sandy siltstone and has some silty limestone and a few beds of silty sandstone. The Ralston Creek and Morrison are made up of varicolored siltstone, silty to sandy claystone, some sandstone, and minor amounts of limestone. Siltstone and claystone of the Ralston Creek are calcareous. South of Morrison (fig. 1), the Ralston Creek contains beds of gypsum and gypsiferous siltstone. The Lytle and South Platte consist of sandstone, clayey siltstone, clayey to sandy claystone, and some conglomeratic sandstone and conglomerate. The Fort Hays is primarily a dense clayey limestone separated by thin beds of calcareous claystone and highly expansive bentonite.

The thickness and lateral continuity of individual beds differs among the various formations. Individual beds of the Lykins and Fort Hays are generally a few centimeters to about a meter thick and are laterally persistent; those of the Fountain, Lyons, Lytle, and South Platte are usually about several centimeters to 10 m thick and are discontinuous; whereas beds of the Ralston Creek and Morrison are about 10 cm to 10 m thick and are laterally persistent or discontinuous.

The degree of induration of the various rock types varies somewhat with the amount and type of interstitial material. Limestones of the Lykins and Fort Hays are generally hard, dense, and cemented by calcium carbonate. Sandstone, conglomeratic sandstone, and conglomerate of the Fountain, Lyons, Lytle, and South Platte are dense, hard, and cemented by silica and iron oxide, but locally they are friable where cemented by calcium carbonate and iron oxide. Siltstone and sandstone of the Lykins, Ralston Creek, and Morrison are firm to hard and are cemented by calcium carbonate, clay, and lesser amounts of iron oxide and silica. Claystone in the various formations is firm and is bonded by clay minerals. Gypsum in the Ralston Creek is soft to firm. Illite, mixed-layer illite-montmorillonite, and kaolinite are the principal clay minerals in claystones of the Ralston Creek, Morrison, Lytle, and South Platte. The Lyons is made up mostly of quartz sand. Sandstone and conglomerate of the Fountain are composed of quartz, feldspar, and minor amounts of rock fragments. Quartz sand and chert pebbles are the chief constituents of the sandstone and conglomeratic sandstone of the Dakota Group. (For additional information, see the lithologic descriptions in the section on "Descriptive outline of rock units.")

PHYSICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

The grain-size distributions and Atterberg limits of the various rock types of the above units are not well known. Limited grain-size data suggest that the sandstones of the Lyons, Lytle, and South Platte are composed of very fine to fine sand that is very slightly silty to silty and clayey. These rocks consist of about 5-25 percent silt and clay and 75-95 percent sand (table 9, this report; McConaghy and others, 1964). Test data for one sample each of siltstone of the Lykins and the Morrison, and claystone of the Laramie indicate that these lithologies differ considerably in clay content and plasticity. Siltstone of the Lykins is 30 percent clay and 70 percent silt, whereas siltstone of the Morrison is 60 percent clay, 30 percent silt, and 10 percent sand. The claystone contains more clay than the siltstones and is composed of 80 percent clay and 20 percent silt (table 9). The siltstones and claystone also have different Atterberg limits and Unified Soil Classification group symbols. The siltstones have a liquid limit of 25 and a plasticity index of 5 or less. Their Unified Soil Classification group symbol is ML. In comparison, the claystone is considerably more plastic. It has a liquid limit of 55 and a plasticity index of 20. Its Unified Soil Classification (U.S. Bureau of Reclamation, 1974) group symbol is MH (table 10).

Rocks of Early Cretaceous age and older tend to be less expansive and have higher bearing capacities than younger rocks of similar grain size. Claystone of the Ralston Creek, Morrison, Lytle, and South Platte produce swelling pressures of less than 75 kN/m^2, compared with about 75-930 kN/m^2 for much of the younger claystone in the piedmont. Siltstones of the Ralston Creek, Morrison, Lytle, and South Platte are less expansive than the claystones of these formations. Siltstones of the Lykins and Morrison have swelling pressures of about 30 and 40 kN/m^2, respectively (table 11). Swelling pressures exerted by thin beds of claystone and bentonite of the Fort Hays, of Late Cretaceous age, are higher than those of most claystone of Early Cretaceous age and older. Swelling pressures of the fine-grained rocks of the Fort Hays Limestone Member are probably comparable with those of similar rock types of the Smoky Hill Shale Member. Massive beds of silica-cemented sandstone and conglomerate, and thick beds of dense limestone have high bearing capacities and can support heavier loads than thinner, less well indurated, or fractured rock of similar lithology.

Nonexpansive to slightly expansive and moderately to strongly indurated sedimentary units commonly have the following performance characteristics: Claystone, siltstone, chalky limestone, and gypsum are easy to moderately difficult to excavate with power equipment, whereas most sandstone, conglomerate, and dense limestone are difficult to excavate and may require blasting. Foundation conditions are generally good except in areas underlain by water-soluble material such as gypsum or gypsiferous siltstone, or thin interlayered beds having different bearing capacities that may be prone to differential settlement. Permeability is highly variable and commonly ranges from very low to low for most claystone and siltstone to moderate to high for sandstone and conglomerate, in areas away from fractured zones and outcrops. Fractured sandstone and conglomerate, especially in outcrop areas, are highly permeable. Limestone usually has low to moderate permeability. Clayey bedrock generally has poor trafficability and is more susceptible to frost heave and erosion than sandstone and conglomerate. Slope stability is usually good on gentle slopes and in undisturbed areas where the bedding is inclined into the slope. Dipslopes and areas where planes of weakness dip into steep cuts are less stable and may produce rock slides and rockfalls. Special precautions against corrosion are needed to protect steel pipe and concrete that are in contact with gypsum or gypsiferous sediments.

IGNEOUS AND METAMORPHIC ROCK UNITS

GENERAL DESCRIPTION

Igneous and metamorphic rocks make up the bedrock of the Front Range, but they are of very limited extent in the piedmont and hogback belt (fig. 2). In the Front Range west of Denver, the major rock types are gneiss, schist, and migmatite, along with lesser amounts of plutonic rocks (granite to granodiorite), and minor amounts of quartzite and felsic to mafic dike rocks (table 1). On the piedmont, igneous rocks make up a minor part of the bedrock and include the shoshonite (Trimble and Machette, 1979b) or monzonite (Van Horn, 1976) dikes near Ralston Reservoir, the shoshonite (Trimble and Machette, 1979b) or latite (Van Horn, 1976) lava flows on North and South Table Mountains, and the Wall Mountain Tuff—a rhyolitic ash flow—which caps many of the buttes south of Castle Rock (fig. 1). In the hogback belt, igneous rocks are rare and consist a few scattered sills and irregular bodies of rhyodacite northwest of Denver. The only exposure of metamorphic rocks in the area east of the Front Range is in the Deer Creek anticline (fig. 1), south of Morrison.

WEATHERING

The physical properties and performance

characteristics of the igneous and metamorphic rocks in the Greater Denver Area are related primarily to the degree of weathering and, in areas adjacent to fault zones or Laramide intrusive bodies, to the amount of recrystallization, cementation, shearing, and alteration. In areas of deeply weathered rock, such as the gently rolling uplands in the mountains west of Denver, fresh, moderately hard to hard crystalline rock containing relatively few fractures is covered by thick regolith. The regolith can be subdivided on the basis of weathering into two parts, which commonly consist of the underlying slightly to moderately weathered rock—characterized by numerous fractures, abundant yellowish iron oxide staining on rocks and mineral grains, reduced shearing strength, and lower bulk density—and the overlying highly weathered rock or saprolite. The saprolite is a product of prolonged physical and chemical weathering and has properties that contrast markedly with those of the underlying weathered and fresh rock. Locally, the regolith has been partly or completely removed by erosion or is buried by younger surficial deposits. The thickness, degree of weathering, and other properties of the regolith often vary over short distances. Some of the major factors that influence its development in crystalline rocks are (1) mineralogy, especially the relative abundance of biotite, (2) steepness of surface topography, (3) relative abundance and orientation of fractures, (4) amount of shearing and (or) hydrothermal alteration (Schmidt and Pierce, 1976), (5) degree of development and orientation of foliation, and (6) length of time that the rock has been exposed to weathering processes. The regolith tends to be thick and extensively weathered in areas where the rock was particularly susceptible to granular disintegration and decomposition, has been relatively unaffected by erosional processes that could have removed the weathering products and exposed fresh rock, and has been subjected to weathering processes for many millions of years.

In general, crystalline rocks in areas of gently sloping terrain or sheared rocks along fault zones or intrusive bodies are more highly weathered or hydrothermally altered than similar rocks in areas of steeply sloping terrain or in areas away from fault zones or intrusive bodies. In areas of gently sloping terrain, away from fault zones or intrusive bodies, strongly foliated rock with numerous, closely spaced, nearly vertical fractures and abundant biotite is much more weathered than nonfoliated, massive rock that is low in biotite. In addition, rocks composed primarily of quartz and potassium feldspar tend to be less weathered than those high in biotite and plagioclase. Comparison of the weathered materials formed from crystalline rocks of varying composition suggest the following sequence of relative stability for the common rock-forming minerals in the near-surface environment: quartz > potassium feldspar > plagioclase ≥ hornblende > biotite (least stable). Besides differences in the amount of weathering among different crystalline rocks, the depth of weathering can vary considerably, even within the same rock body. Typically, it is shallowest in massive rock and deepest along closely spaced, open fractures. Deep weathering is common in coarse-grained granitic rock, especially the Pikes Peak Granite, where locally it extends to depths of greater than 50 m (Blair, 1975).

In this section, crystalline rocks unaffected by faulting and igneous intrusion are grouped, on the basis of weathering characteristics, into the following categories: (1) units commonly overlain by thick, slightly to highly weathered regolith, (2) units commonly overlain by thin, slightly to moderately weathered regolith, and (3) units commonly overlain by thin and discontinuous, unweathered to slightly weathered regolith; a fourth category— units affected by faulting and igneous intrusion—includes those crystalline rocks that are cut by faults and Laramide intrusive rocks.

UNITS COMMONLY OVERLAIN BY THICK, SLIGHTLY TO HIGHLY WEATHERED REGOLITH

GENERAL DESCRIPTION

Gneiss, schist, migmatite, granite, quartz monzonite, granodiorite, and amphibolite are widespread in the mountains west of Denver. These rocks are of Precambrian age and are composed of various amounts of potassium feldspar, plagioclase, quartz, mica (mainly biotite), and hornblende. Commonly, they are mantled by thick regolith, which grades from saprolite in the upper part to moderately to slightly weathered rock in the lower part. The regolith consists of varying amounts of weathered rock fragments in a sandy matrix that ranges from clean, coarse sand to clayey, fine to coarse sand. At stable sites, the saprolite usually extends deeper than 3 m, and fresh bedrock commonly occurs at depths of less than 30 m. The fresh bedrock is nonfoliated to strongly foliated, nonlayered to layered, massive to slightly fractured, and moderately hard to very hard. It tends to have fewer fractures and much less iron oxide staining than the overlying weathered rock.

PHYSICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

Available test data indicate that regolith derived from gneiss, schist, and granitic rocks has fairly similar grain-size distributions and plasticity characteristics. Particles of weathered gneiss and schist, less than 64 mm in size, are composed of about 10 percent silt and clay, 40 percent sand, 15 percent granules, and 35 percent pebbles (table 9). In comparison, the same size fraction for weathered granitic rocks consists of about 5 percent silt and clay, 35 percent sand, 25 percent granules, and 35 percent pebbles. The amount of cobble- and boulder-size rock fragments tends to increase with depth; they commonly make up about one-half or less of the upper several meters of the regolith. Weathered material, less than 0.4 mm in size, from gneiss, schist, and granitic rocks is nonexpansive, has a liquid limit of about 20–30, and is nonplastic (table 10). Much of the regolith derived from the above rock types would probably be classified, according to the Unified Soil Classification (U.S. Bureau of Reclamation, 1974), as well-graded gravel (GW).

Gneissic, schistose, granitic, and amphibolitic rocks and the overlying regolith commonly have the following performance characteristics: The regolith is usually easy to moderately easy to excavate with power equipment, but the underlying unweathered bedrock is moderately difficult to difficult to excavate and usually requires blasting. Foundation conditions are generally excellent on the unweathered bedrock; however, conditions range from good on weathered gneiss, migmatite, and granitic rocks to fair on weathered amphibolite and schist. Permeability is commonly moderate to high in the saprolite and along fractures in the weathered rock and is relatively low in the unweathered bedrock. Regolith on steep slopes and in areas where the vegetation has been disturbed or removed is susceptible to sheet erosion and gullying. Gentle slopes generally are stable; debris slides and rockslides may occur locally on steep slopes or in areas where the rock is intensely fractured or highly weathered, or the foliation parallels the slope.

UNITS COMMONLY OVERLAIN BY THIN, SLIGHTLY TO MODERATELY WEATHERED REGOLITH

GENERAL DESCRIPTION

Shoshonite, rhyolite, and rhyodacite, of Paleocene and Oligocene age, are very minor components of the bedrock in the piedmont and hogback belt, whereas quartz monzonite, monzonite, latite, and diabase, of Late Cretaceous to Eocene(?) age, make up a small amount of the bedrock in the Front Range. These volcanic and shallow-intrusive rocks are composed of varying amounts of felsic and mafic minerals: rhyolite, quartz monzonite, and rhyodacite consist primarily of quartz, potassium feldspar, plagioclase, and (or) biotite; monzonite and latite are made up mostly of potassium feldspar, plagioclase, biotite, and (or) hornblende; and diabase and shoshonite (potassium-rich basalt) are formed mainly of plagioclase and augite. These rock types are commonly mantled by regolith that is considerably thinner and much less weathered than that developed on granitic and gneissic rocks. The upper part of the regolith commonly consists of slightly to moderately weathered rock and little or no saprolite. The lower part is only slightly weathered, mostly along fractures. The underlying fresh bedrock is typically nonfoliated, massive to slightly fractured, and hard to very hard. These rock units are tabular bodies that range in thickness from less than 1 m to about 600 m for intrusive rocks and about 5 to 70 m for volcanic rocks.

PHYSICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

The grain-size distribution and plasticity characteristics of regolith derived from lava flows, tuff, and dike rocks are not well known. The regolith formed from these rocks probably contains more granule- to boulder-size material and less silt and clay, and probably has a lower liquid limit and is less plastic than the weathered mantle on gneiss, schist, and granitic rocks.

Volcanic and shallow-intrusive rocks and the overlying regolith commonly have the following performance characteristics: The regolith is moderately easy to excavate with power equipment, but the underlying fresh bedrock is moderately difficult to difficult to excavate and locally requires blasting. Foundation conditions are excellent on the unweathered rock and generally are good on the regolith. Permeability tends to be low to moderate along fractures in the intrusive rocks and moderate to high in the regolith and along fractures in the lava flows and tuff. Slope stability is generally good on the intrusive rocks, but poor to fair for volcanic rocks, which commonly cap steep-sided buttes and mesas and are prone to debris sliding and rockfall.

UNITS COMMONLY OVERLAIN BY THIN, DISCONTINUOUS, UNWEATHERED TO SLIGHTLY WEATHERED REGOLITH

GENERAL DESCRIPTION

Precambrian pegmatite and quartzite are associated with other crystalline rocks of the Front Range. Pegmatite dikes are common features in areas underlain by granitic, schistose, and gneissic rocks. Quartzite, which includes conglomeratic quartzite and some conglomerate, is much less common except in the area adjacent to the lower part of Coal Creek Canyon (fig. 1). Both pegmatite and quartzite are rich in quartz and commonly contain little or no biotite, although biotitic pegmatite occurs locally. Most pegmatites are composed primarily of quartz, potassium feldspar, and muscovite, whereas, quartzite is made up of quartz and a minor amount of muscovite. Because of their stable mineralogic compositions, quartzite and most pegmatites are very resistant to weathering and often form unweathered outcrops. Regolith, where present, is thin and patchy and consists of angular rock fragments of varying sizes in a sandy matrix that is very low in silt and clay. The regolith shows little or no evidence of chemical weathering and is usually less than about 1-2 m thick. The underlying bedrock is fresh, massive, and very hard; the quartzite is foliated and layered, whereas the pegmatite is not. These rock types range in thickness from about 10 cm to 70 m for dikes and lenticular bodies of pegmatite to as much as about 1,000 m for quartzite.

PHYSICAL PROPERTIES AND PEFORMANCE CHARACTERISTICS

Very little is known about the grain-size distribution and plasticity characteristics of regolith formed from pegmatite and quartzite. They may be somewhat similar to those for regolith derived from volcanic and shallow-intrusive rocks.

Pegmatite and quartzite and the overlying regolith commonly have the following performance characteristics: The regolith is moderately easy to excavate with power equipment, but the fresh bedrock is very difficult to excavate and usually requires blasting. Foundation conditions are excellent on the bedrock and generally are good on the regolith. However, conditions may be fair to poor on loose regolith that has large voids and a low amount of stone-to-stone contact. Permeability tends to be very high in the regolith and low along the tight fractures in the bedrock. Slope stability is usually good, although rockfalls may develop locally on steep slopes and in highly fractured rock.

UNITS AFFECTED BY FAULTING AND IGNEOUS INTRUSION

GENERAL DESCRIPTION

Crystalline rocks along and within fault zones and adjacent to intrusive bodies of Late Cretaceous to early Tertiary age commonly have properties that differ greatly from those of the same rock mass beyond the influence of tectonic and (or) igneous activity. Faults ranging from single fractures to broad shear zones hundreds of meters wide are common structural features in the Front Range west of Denver (Tweto and Sims, 1963). Individual faults vary considerably in length and width and can end gradually or terminate abruptly against unfractured rock. Material within fault zones is highly variable and ranges from recrystallized breccia to massive blocks of unbroken rock bounded by masses of highly sheared and altered rock fragments in a matrix of sandy clay. Fault zones composed of sheared and altered rock usually form saddles or valleys, whereas fault zones that are silicified or recrystallized tend to be more resistant than the adjacent rock and locally form narrow, linear ridges. Veins, dikes, and stocks are commonly emplaced along faults and other zones of weakness. Rocks adjacent to these bodies also show differing amounts of tectonic deformation and chemical alteration. In general, alteration near faults and along contacts with intrusive rocks is less extensive in granitic rocks than in metamorphic rocks that have high contents of biotite, calcic plagioclase, and (or) hornblende.

PHYSICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

Owing to the considerable range in the degree of recrystallization, cementation, shearing, and alteration, faulted and intruded rocks commonly have a wide array of physical properties and performance characteristics. These properties and characteristics vary from those of well-indurated, recrystallized fault breccias, which are similar to unweathered granitic and gneissic rocks, to those of highly sheared and altered metasedimentary rocks, which are similar to saprolite.

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