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

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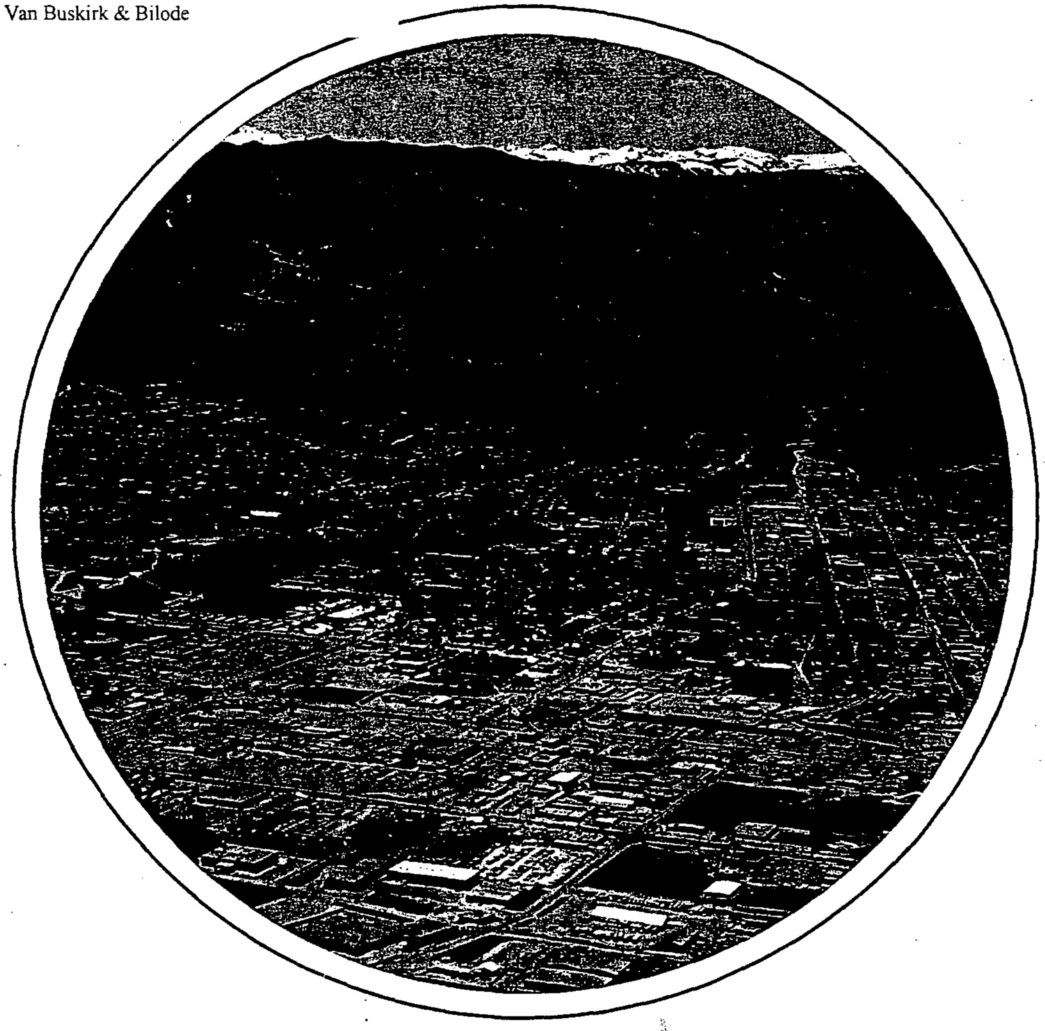
a report of geologic influences on the location, development, and future of the Boulder metropolitan area



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Geology of Boulder, Colorado, United States of America

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FOREWORD

Boulder—as substantial and heartwarming a name as any geologist could hope for in a city! This name, bearing all of the substance of geology, stands now for a city that has perhaps coaxed all of the maximal benefits from an overbearing geological surrounding, yet has to answer to only a moderate degree of geologic constraint.

Boulder came to be, similar to many New World cities, as a convenient place from which to search for fortune. Prospectors chose this hospitable location because of its decent climate, ready supply of surface water, and accessibility to the nearby mountainous mineral regions. Mid-19th century gold discoveries sealed the fortune of Boulder, which became a town in only one year (1859) and the site of the proposed University of Colorado within another three years.

Though Boulder lies but 43 km northwest of Denver, its larger neighbor (see AEG *Bulletin,* Vol. XIX, No. 3, 1982), it marches to the tune of different drummer. Like Denver, the convenient location between prairie to the east, and great mountains to the west, has the shaped the city's development. Boulder's dependence on these mountains began with its initial use of stream water, and became soundly established with its first of many acquisitions of mountain land for parks (1898) and for water supply (1898). These mountain slopes are now incontrovertably the property of all citizens and will not likely be altered by hillside development. Boulder residents are, by and large, relatively young and are naturally mindful that unbridled growth may not be wholly desirable. These citizens have chosen to regulate the rate at which the city grows.

The surrounding Boulder County, however, has become the population sorption mechanism and is now half-again more populous than the city. Both units have come to realize that cooperation in government is essential. Much of the geologic overtones of growth and development are now managed cooperatively between city and county.

Boulder geology encompasses a variety of rock types and geologic terranes. Precambrian crystalline rocks underlie the western edge of the city which rises abruptly toward the Rocky Mountains. These rocks are in unconformable and fault contact with a gently rolling terrain underlain by tilted sedimentary rocks of upper Paleozoic to upper Mesozoic age.

The city floor lies mainly on Quaternary alluvium and Cretaceous-aged claystone and shale, with interbeds of sandstone and conglomerate. The claystone and shale in this series are commonly expansive. Seven types of surficial deposits mantle the bedrock, the most common of these are a series of weathered pediment alluvial units containing the numerous boulders which gave the city its name.

The majestic mountains are the focus of a good deal of discussion relating to regional seismicity. Rocky Mountain uplift is no longer thought to be an over-and-done-with Laramide event. As the range is now regarded as the northern extension of the Rio Grande rift, this tectonism may well have been reactivated in late Miocene time, and may also have experienced major uplift during Pliocene-Holocene time. These revelations make less comforting the traditional geologic presumption that regional seismicity is essentially of low magnitude. Candidates for *capable* faults have been discovered within the county, and as close as 16 km to Boulder.

Remote potential for earthquake.

Among its geologic blessings, Boulder counts a plentiful supply of sand and gravel. Though over a third of this resource has been compromised by urban development, comprehensive planning and zoning has reached to protect the remaining reserves. This same planning and zoning, among the most advanced east of west-coast America, is exercised at both the city and county level and recognizes the need to regulate resources and to respect geologic constraints and natural hazards. Flood plains are now zoned, but remain subject to disastrous cloudburst discharge from storms centered in the mountains. Planning and/or zoning policies have been extended to wetlands, to areas of slope instability, and to areas of potential soil swell and collapse. Sand and gravel extraction pits are reclaimed as an obligation of regulatory permitting.

There are extraction sites for cement-grade limestone, dimension stone, oil and gas, and some metals within the county. Coal mining, once extensively worked in the Front Range, has ceased as of 1976, leaving significant areas of subsidence hazards near Boulder.

Boulder is one of the relatively few American cities that has developed a full engineering and environmental geologic data base from which to guide its growth and development. Both city and county have benefited enormously from the nearby Colorado Geological Survey (CGS) and the U.S. Geological Survey (USGS). Most of the hazards maps and geological constraints identification, and resources-based zoning measures draw their basic information from published and unpublished data developed by these organizations.

Boulder County concerns for meeting geologic and natural resource constraints additionally deal with coal-mine subsidence, fires in abandoned mines, and mineral extraction. Due to statutory and the USGS influence, a City Geologist (1969–1979) and a County Geologist (1976–1980) were employed in developing a distinct series of unpublished "hazards maps" that are available for use and reference at the respective government offices. The surveys remain in support of the city and county. The Colorado Survey, in particular, devotes part of its small staff to review development plans for the city and county on an as-requested basis.

Geotechnical practice favors west-coast methods, especially in terms of field exploration methods and laboratory testing. Much of this influence relates naturally to the influences of the normally-consolidated nature of most Boulder area soils. Shallow to intermediate depth concrete foundations serve for most structures, which are limited in height to medium rise (seven stories). The city's frequent near-surface ground-water conditions lead to the use of sheet piling for construction excavations. Geotechnical practitioners have been in the forefront of their profession by developing and implementing their own as well as worldwide remedial technology to combat potential soil expansion and collapse damage to engineered structures.

Environmental engineering concerns are dominated by the need to manage solid waste and waste water treatment sludge. Landfill disposal facilities located in the county, have led to some instances of degradation of surface water and ground-water quality. One sanitary landfill is now targeted for Superfund remediation of hazardous wastes co-disposed with municipal refuse.

All bodes well for Boulder, in geologic terms. The city is well informed of its geologic environment; it cannot mentally escape its mountain-back reminder of those influences, it cooperates with its county in management of these resources and constraints, and it has three-sides-room for slow-paced expansion, under pressures of urban development.

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ABSTRACT

Boulder, Colorado is situated in one of the most scenic areas along the Front Range of the Southern Rocky Mountains. The city is located on the western edge of the Denver Basin and is surrounded by the economic mineral deposits that first brought development to the area: gold and silver to the west, coal, oil and gas to the south, east and north. Sand and gravel deposits have been identified and a county wide master plan has been developed for their extraction. In spite of the city's and county's far-sighted and informed leadership, some problems relating to geologic and hydrologic processes have occurred. Marshall Landfill, a solid waste disposal facility, has so seriously contaminated surface and ground water with hazardous waste that it is on the U.S. Environmental Protection Agency's Superfund Cleanup list. The first phase of remedial action taken at this site cost nearly a half million dollars. Much of the city is built within flood plains and significant property damage is expected in the event of a 100-yr or larger flood. Expansive and collapsible soils cause a significant amount of property damage each year although design solutions are well known and effective if constructed properly. Numerous landslides and debris flows have occurred within the city causing damage and are likely to cause more damage in the future. South of the city there are numerous abandoned underground coal mines. Subsidence over these mines has become a problem as housing development moves into the area. Boulder is addressing these geologic and hydrogeologic hazards through city, county, and state programs aimed at identifying and quantifying the hazard and implementing governmental regulation designed to discourage irresponsible land use.

INTRODUCTION

Boulder, Colorado is located 43.4 km (27 mi) northwest of Denver at the base of the foothills of the Rocky Mountains (Figure 1). The population of Boulder in 1985 was approximately 80,000. Since Boulder serves as the hub of activity and as the county seat, this paper includes significant geologic considerations in the county wide area which impact the city's overall growth.

Elevations in Boulder County range from 1,495 m (4,900 ft) above mean sea level to 4,345 m (14,256 ft) at Longs Peak on the Continental Divide, which serves as the county's western border. The City of Boulder is located at elevation 1,629 m (5,340 ft), but elevations increase rapidly to the west in the foothills and beyond. The geographic center of the city is located at 40°00′N latitude and 105°16′W longitude (Figure 1).

Storage Technology, IBM, and the University of Colorado are the major employers in Boulder County, employing over 16,700 people as of 1980 (Boulder Chamber of Commerce, 1980). Boulder is an internationally recognized site for research and development work. It is one of the world centers for research in the atmospheric sciences, hosting facilities for the National Center for Atmospheric Research (NCAR), the National Oceanographic and Atmospheric Administration (NOAA), the Joint Institute for Laboratory Astrophysics and the Environmental Sciences Services Administration Research Laboratory.

History of Founding

On October 15, 1858, Captain Thomas Aikins and about 20 prospectors established a camp at the mouth of Boulder Canyon. They were the nucleus for the first white settlement established in the area. Originally, Captain Aikins had intended to go to the Cherry Creek diggings west of Denver, but when he saw Boulder Valley he decided to settle there. In January 1859, gold was discovered at Gold Run Creek in the mountains west of Boulder. This brought many prospectors into the area. The Gold Hill Mining District quickly became a major gold producing center in the Rocky Mountains. The Boulder City Town Company was founded on February 10, 1859. The settlement was named after the numerous boulders that were and are still present on the area's alluvial surfaces and terraces. They divided the land north of Boulder Creek into 4,044 lots for sale at $1,000 each. Despite the enthusiasm of this first group of real estate investors, $1,000 was a considerable sum of money at the time and many new arrivals chose to continue west into the mountain towns or to settle on farm lands east of Boulder. Prior to the arrival of the white man, Arapahoe Indians roamed and hunted in the area. By the early 1860's, most of the Indians had drifted away as hunting became more difficult with increasing development of the area.

In 1862 Boulder was named as the site of the future University of Colorado. On November 4, 1871, Boulder was incorporated as the "Town of

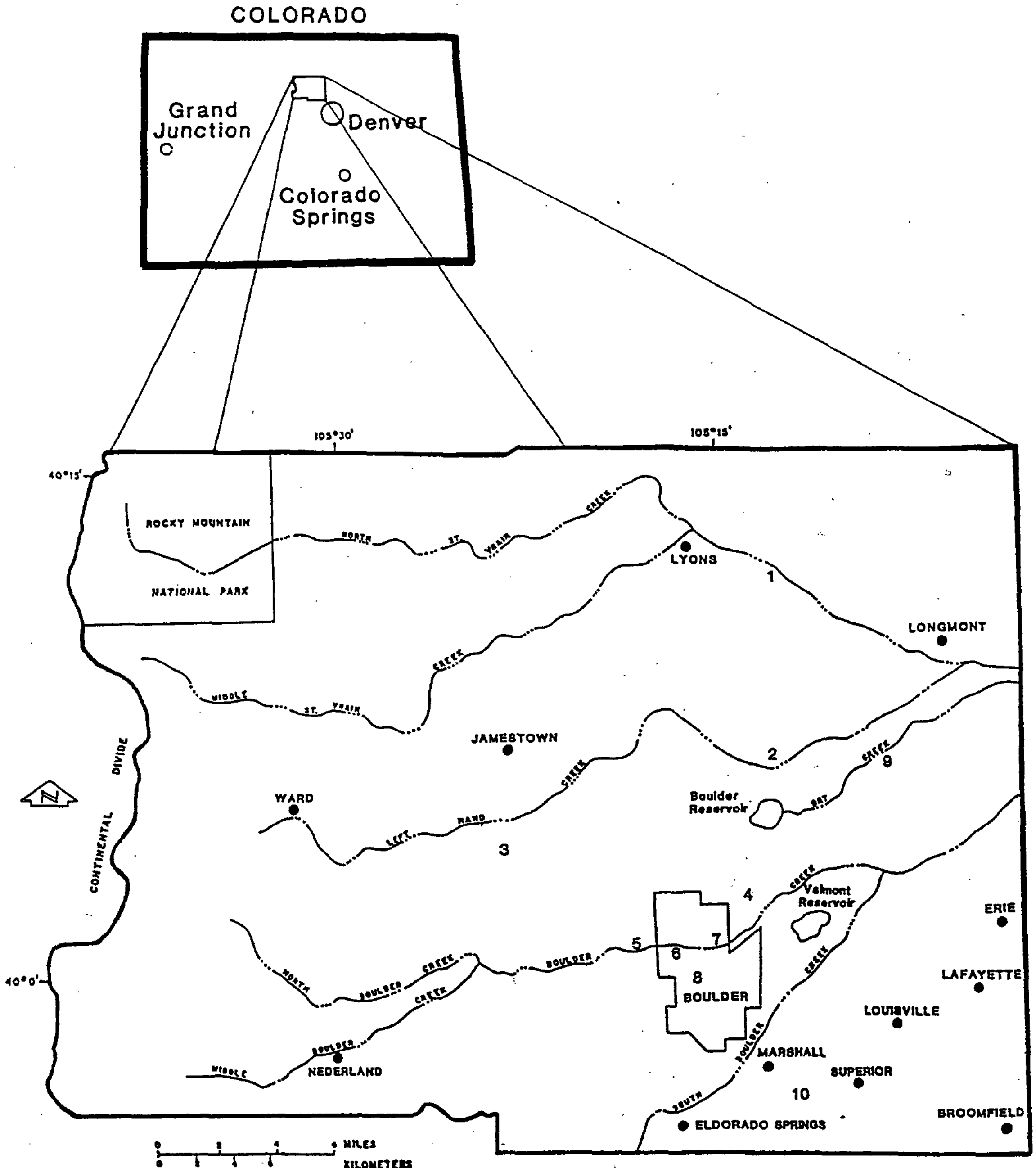


Figure 1. Location map of the City of Boulder, Boulder County, and features in Boulder County mentioned in the text. 1) Martin Marietta limestone quarry and cement plant, 2) Haystack Butte warm water well, 3) Gold Hill mining district, 4) Gunbarrel area, 5) location of large boulder in Boulder Creek in Figure 18, 6) location of municipal building in Figure 19, 7) location of the bank building in Figure 20, 8) University of Colorado campus, 9) location of Walden Ponds Wildlife Habitat and active gravel pits in Figure 15, 10) Marshall landfill.

Boulder." During the next decade the population jumped from just a few hundred to more than 3,000, largely because of the completion of the Colorado Central Railroad. The population in the City of Boulder was 6,000 in 1900, 10,000 in 1910, and about 11,000 in 1920. The present explosive growth began after World War II. In 1976, the City of Boulder made headlines by officially adopting a policy to limit growth to 2 percent per year. This policy is still in effect and is implemented through the allo-

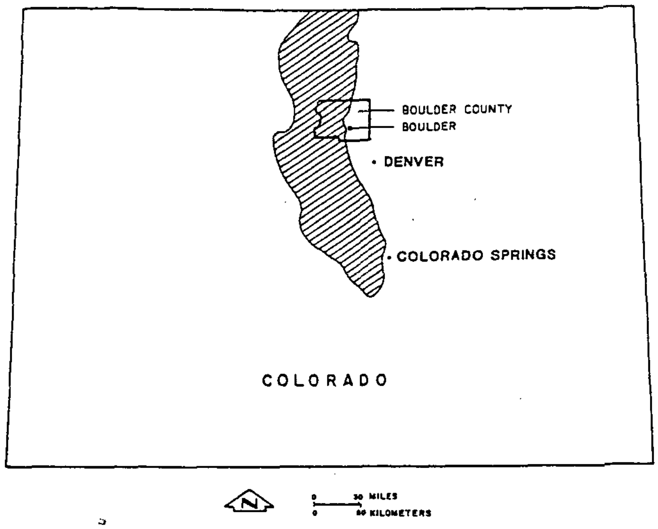


Figure 2. State of Colorado showing the Front Range (ruled) in relation to Boulder and Boulder County.

cation of building permits. The population of Boulder County is now over 200,000 people, with more than 80,000 in the city proper. The population is considered young, over 50 percent of the people are less than 30 years old (Boulder Chamber of Commerce, 1980).

Acquisition of mountain land by the city began in 1898 with the purchase of 80 acres. In 1899 and 1907, Congress granted the city an additional 1,780 acres of land on Green Mountain, Bear Mountain and Flagstaff Mountain. These lands, together with later purchases, comprise a "greenbelt" of public land which surrounds Boulder and guarantees a permanent backdrop of undeveloped mountain scenery.

Climate

Boulder has a semiarid, continental climate. Winters are cold and dry and summers are cool and relatively dry. The climate is characterized by intense sunlight, low humidity, relatively low precipitation, occasional high winds and large temperature fluctuations. The annual mean temperature is 10.4°C (50.7°F), with a mean summer temperature of 18.7°C (65.6°F) and a mean winter temperature of 3.4°C (38.1°F). The annual precipitation is 46 cm (18.1 in.), most of which falls in early spring. The prevailing winds at Boulder blow in from the west. These westerly winds are profoundly influenced by the topography provided by the eastern flank of the Rocky Mountains. Cold dense air flows over the crest of the mountain range and accelerates and warms as it flows down the eastern side. The valleys act as vortices that channel the wind and cause even greater velocities. Portions of the city have experienced gusts of winds in excess of 193 km/hr (120 mi/hr). Seasonally, these "chinook" winds have caused damage to building roofs and windows.

GEOLOGIC SETTING

The City of Boulder is located at the eastern edge of the Front Range, the easternmost range of the Southern Rocky Mountains (Figure 2). This location also places Boulder at the western edge of the Denver Basin, one of the largest structural foreland basins in the Rocky Mountains. Originally, the city was built at the mouth of Boulder Canyon where Boulder Creek leaves the Front Range and enters the Colorado Piedmont Section of the Great Plains. Since it was founded, Boulder has expanded only a short distance westward into the mountains, with most of its growth eastward across the plains. Thus, the westernmost part of the city is underlain by Precambrian igneous and metamorphic rocks, while the greater part of Boulder is underlain by upturned late Paleozoic and Mesozoic sedimentary rocks that dip up to 50° east (Figures 3, 4 and 5), and are partly covered by a thin layer of Quaternary surficial deposits (Wrucke and Wilson, 1967; Wells, 1967).

Just 32 km (20 mi) due west of Boulder, the Continental Divide lies along the crest of the Front Range, with elevations reaching 4,115 m (13,500 ft) in the Indian Peaks Wilderness Area south of Rocky Mountain National Park. Longs Peak, at 4,345 m (14,256 ft), is the highest point in the county and is

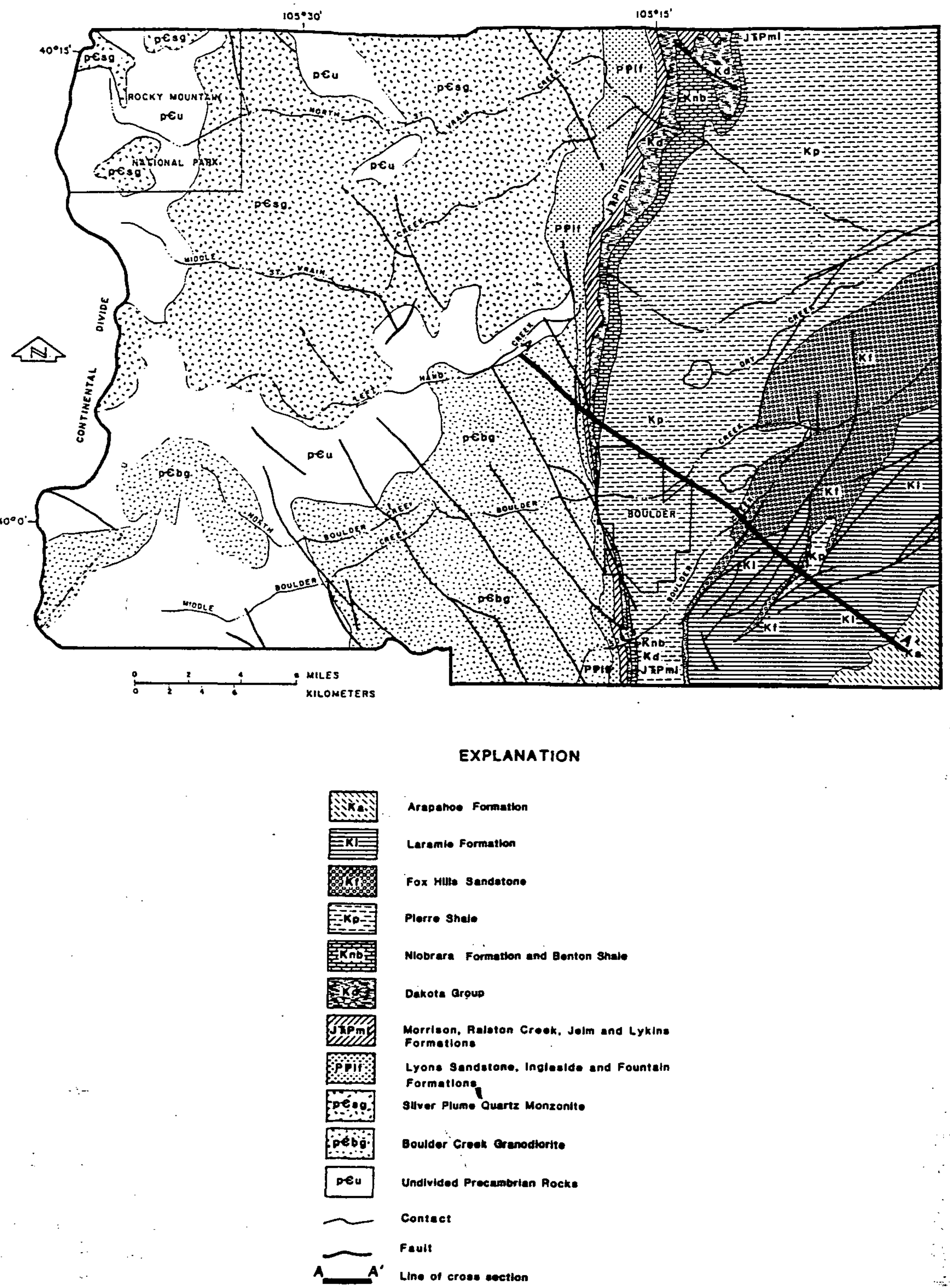


Figure 3. Generalized bedrock geologic map of Boulder County, adapted from Wrucke and Wilson (1967), Wells (1967), Trimble (1975), and Hall and others (1980).

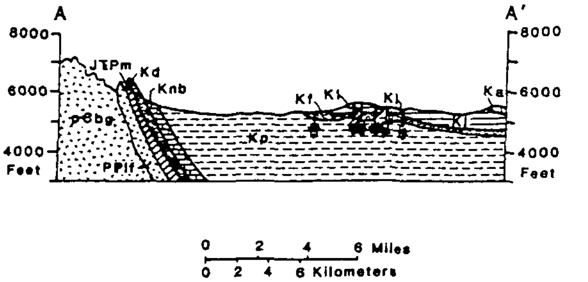


Figure 4. Generalized NW-SE geologic cross section across Boulder. Location shown as A-A' on Figure 3. See Figure 3 for explanation of symbols. Adapted from Hall and others (1980).

located in the extreme northwest corner of the Park. This part of the Front Range is composed primarily of Precambrian granitic rocks intruded into an older suite of metasedimentary and metavolcanic rocks. Cutting this Precambrian terrane is the Colorado Mineral Belt, a narrow northeast-trending zone that contains most of the major mining districts of Colorado. The belt extends from Durango, Colorado in the southwest to the Boulder area in the northeast. The mineralization in the belt is related to stocks, dikes and sills of Lake Cretaceous-Early Tertiary (Laramide), and middle Tertiary age that intruded a major northeast-trending Precambrian shear zone (Tweto and Sims, 1963; Romberger, 1980). Structural elements of this Precambrian shear zone are thought to project northeastward beneath the Denver Basin and may have been reactivated several times during Phanerozoic time, providing structural traps for hydrocarbon resources discovered in the area. This shear zone crosses the southeastern corner of Boulder County (Figure 3) and may also have played a significant part in localizing the extensive coal deposits of the Boulder-Weld Coal Field (Davis and Weimer, 1976).

The mountains of the present-day Front Range, as well as the entire Southern Rocky Mountains, attained their lofty elevations and dramatic relief in Neogene times and should not be considered Laramide age (Late Cretaceous-Early Tertiary) mountains as they are commonly regarded (Bilodeau, 1987). This misconception has been fostered over the years by the intense study of the pervasive Laramide age deformation, igneous intrusion and mineralization found throughout the region. During the Laramide orogeny there were mountains present in the region, but they had a more subdued topography since erosion and sedimentation kept pace with the uplift of the mountain blocks and subsidence in the basins. By the Late Eocene, a low relief erosion surface was present across the entire region (Epis and Chapin, 1975; Epis et al., 1980; Colman, 1985; and Scott and Taylor, 1986). This erosion surface has been subsequently uplifted and locally broken up throughout the Southern Rocky Mountains by Neogene high-angle normal faulting. This uplift, which is still continuing (Kirkham and Rogers, 1981), and its accompanying erosion, has produced the elevation and relief of the present-day Rocky Mountains (Izett, 1975; Scott, 1975; Taylor, R. B., 1975; Epis et al., 1980; and Trimble, 1980). This uplift is related to the northward propagation and evolution of the Rio Grande Rift, a major Neogene extensional feature of crustal dimensions in central New Mexico and Colorado (Riecker, 1979; Cordell, 1982; and Colman et al., 1985).

The Denver Basin, which underlies Boulder, is a large north-south-trending asymmetric structural basin with a gently dipping east flank, that formed during the Laramide orogeny. The City of Boulder is spread out across the eroded and truncated edge of a steeply east-dipping stratigraphic section of middle Pennsylvanian through Late Jurassic nonmarine clastic sedimentary rocks overlain by Cretaceous marine deposits about 3,640 m (11,942 ft) thick (Figure 4). Along the mountain front, from the mouth of Boulder Creek southward, several formations and over 450 m (1,476 ft) of section have been faulted out along the north-northwest-trending Boulder Fault (Wrucke and Wilson, 1967; Wells, 1967). No Laramide age sedimentary rocks are preserved within the city limits of Boulder, though they are present only 8 km (5 mi) to the southeast, near Broomfield.

Bedrock Geology and Geologic History

Precambrian crystalline rocks make up most of the western half of Boulder County and underlie the westernmost fringe of the City of Boulder itself (Figures 3 and 5). These Precambrian rocks consist of folded metasedimentary and metavolcanic gneisses and schists about 1,800 m.y. old that were intruded twice by Precambrian rocks: the Boulder Creek Granodiorite, about 1,700 m.y. old; and the Silver Plume Granite about 1,400 m.y. old. Precambrian fault trends are predominantly north-northwest with a subsidiary set of faults and shear zones that trend northeast. These faults have been reactivated repeatedly throughout Phanerozoic time (Wells, 1967; Tweto, 1980).

The lower Paleozoic section, Cambrian through

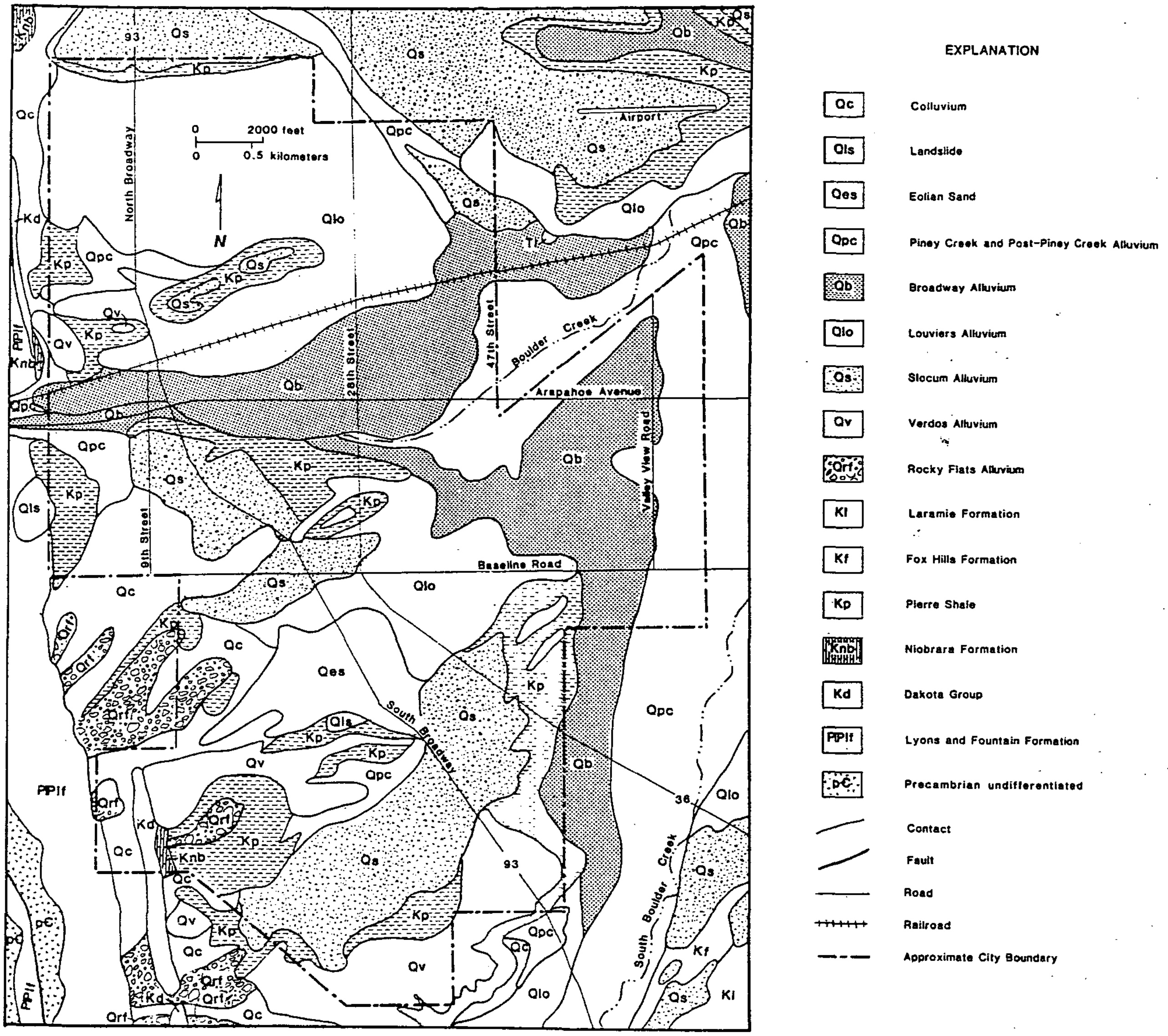
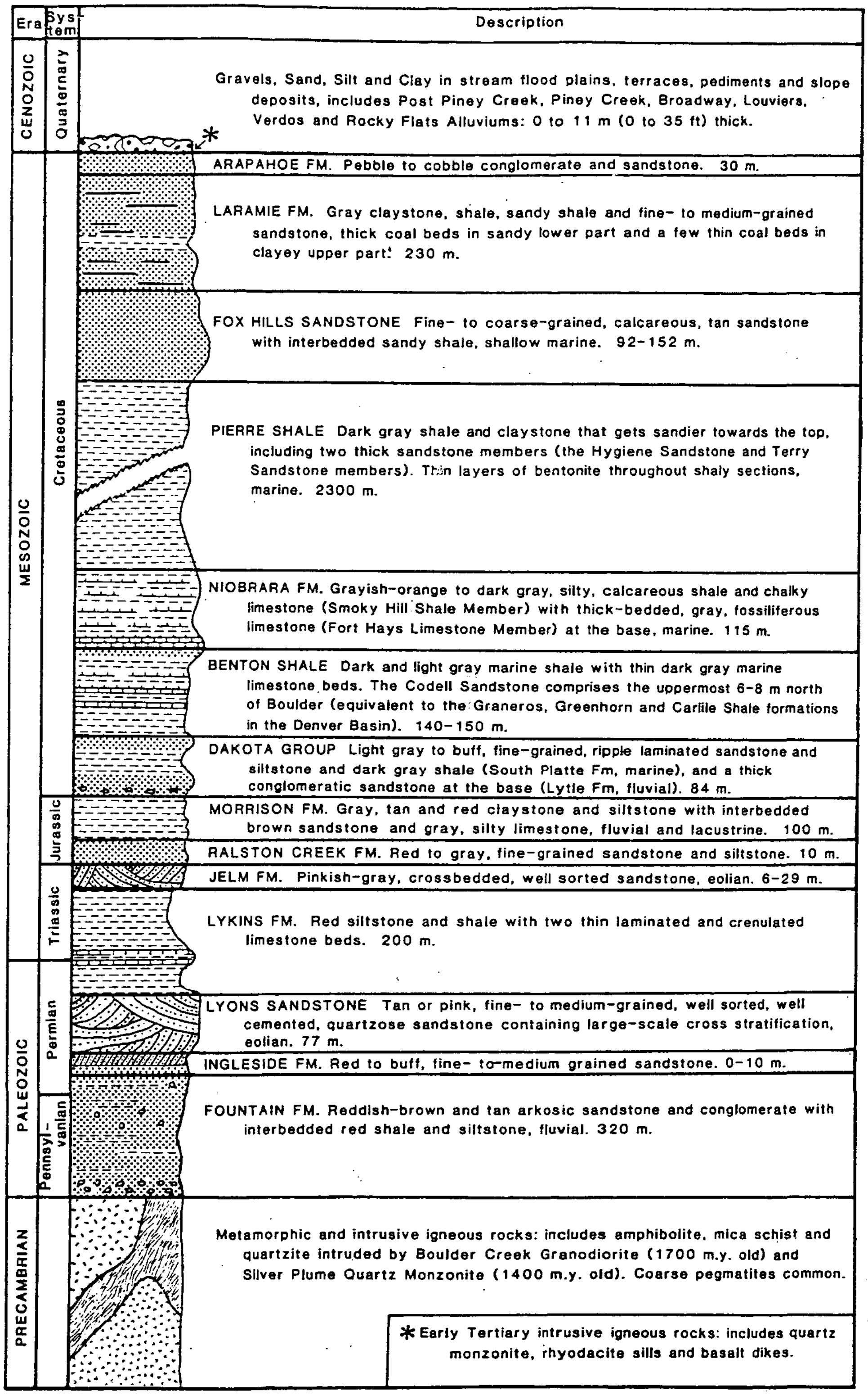


Figure 5. Geologic map of the City of Boulder. Adapted from Spencer (1961), Wrucke and Wilson (1967), Wells (1967), Trimble (1975), Colton (1978), and Trimble and Machette (1979).

Mississippian, is missing in the Boulder area (Figure 6). Here, Pennsylvanian rocks rest unconformably on Precambrian basement. Although the closest lower Paleozoic rocks are on the western side of the Front Range and about 80 km (50 mi) to the south, beneath the Denver Basin, it is thought that lower Paleozoic marine rocks once covered the Precambrian terrane in the area (Ross and Tweto, 1980). Blocks of Cambrian through Devonian age limestone and sandstone have been discovered in a series of diatremes 100 km (62 mi) to the north at the Colorado-Wyoming border, in an area where no lower Paleozoic strata are known (Chronic et al., 1969). This suggests that early Paleozoic marine seas transgressed across the region from time to time. By Early Pennsylvanian time, the Boulder area was uplifted and became situated on the northeastern flank of the Ancestral Front Range uplift, one of several northwest-trending mountain ranges that comprised the late Paleozoic Ancestral Rocky Mountains (DeVoto, 1980; Maughan, 1980). This mountain building episode was the result of reactivation of Precambrian basement structures caused by the continent-continent collision in progress to the southeast. This plate collision, involving the African-South American plate and the southern mar-



unconformity

Figure 6. Stratigraphic column for Boulder County. Adapted from Malde, (1955), Wells (1967), Wrucke and Wilson (1967), and Madole (1973).

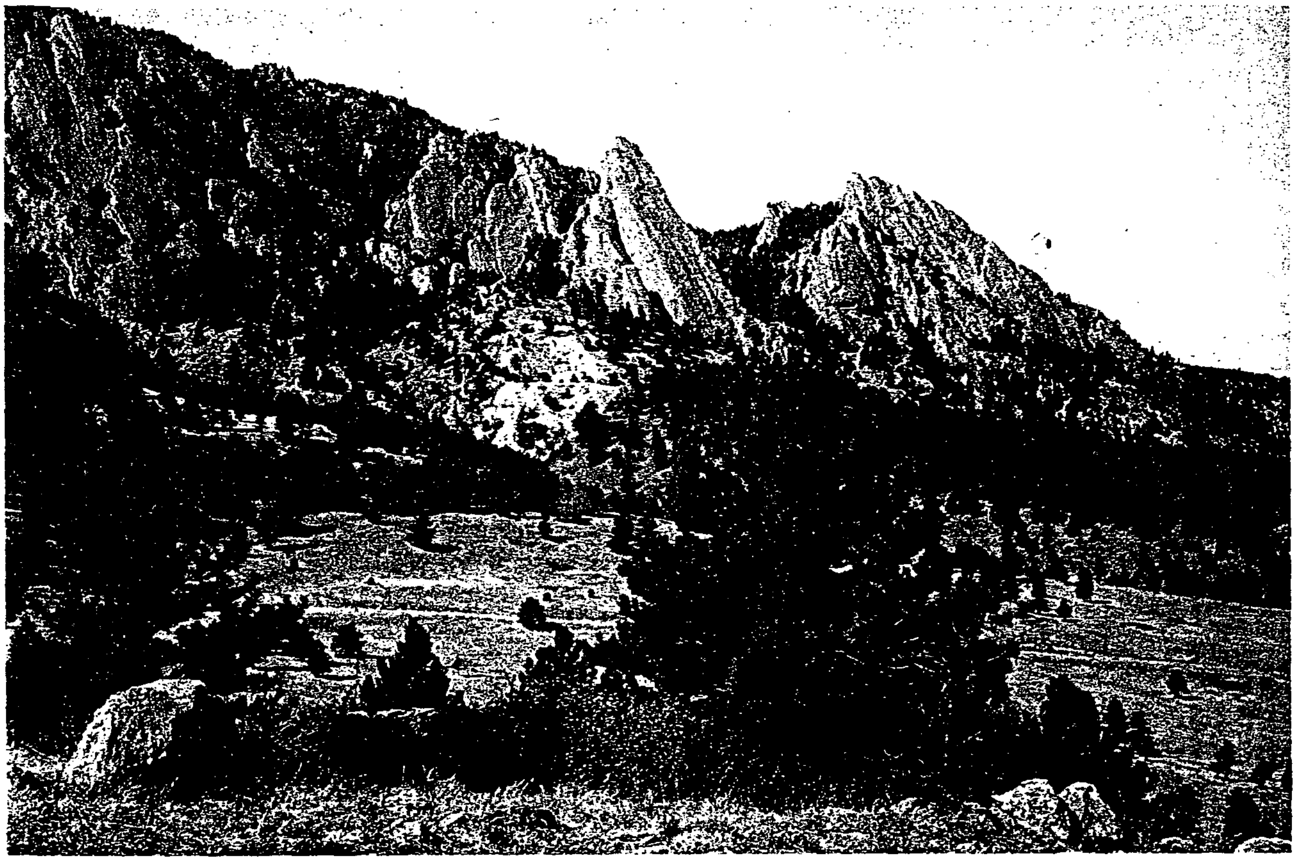


Figure 7. Flatirons of the Fountain Formation just southwest of downtown Boulder.

gin of the North American plate (Kluth and Coney, 1981), has been termed the Ouachita orogeny. Uplift of the Ancestral Front Range caused erosion of the lower Paleozoic section and deposition of the conglomerate and arkose of the mid-Pennsylvanian Fountain Formation. This formation makes up the Flatirons, the prominent rock formations for which Boulder is famous (Figure 7). By the end of the Paleozoic, the Ancestral Front Range was a low-standing set of hills with eolian sandstone, finer-grained nonmarine and marginal marine redbed clastics being deposited in the area.

In the Early Cretaceous, the entire region began to subside due to crustal loading to the west in the developing backarc Sevier fold and thrust belt (Jordan, 1981). A major marine transgression into this subsiding foreland basin produced the intracontinental Cretaceous Interior Seaway (Kauffman, 1977). Both the Ancestral Front Range and the Denver Basin area became buried under about 3,000 m (9,842 ft) of marine and marginal marine strata of Cretaceous age (Figure 6). Most excavations within the City of Boulder will encounter the Late Cretaceous Pierre Shale as bedrock beneath thin Quaternary alluvium (Figure 5). With a thickness of around 2,300 m (7,546 ft), this marine shale is the thickest stratigraphic unit in the Boulder area (Figure 6).

At the end of the Cretaceous Period, this large foreland basin began to break up with the formation of basement-cored, thrust and reverse fault-bounded uplifts and smaller intermontane basins. This Late Cretaceous-Early Tertiary tectonic episode is called the Laramide orogeny. Beginning about 67.5 m.y. ago (Tweto, 1975), a mountain range with much the same configuration as the present Front Range was uplifted, contributing to the formation of the Denver Basin to the east (Bilodeau, 1987). Erosion of sedimentary strata from the rising Laramide Front Range kept pace with the rate of uplift and deposition in adjacent basins so that the actual topographic relief of the mountains was never great, much less than in the Rockies of today. By the Late Eocene, uplift had ceased and a regional, low-relief erosion surface was developed across the area of both the uplifts and the basins (Epis et al., 1980). Most of the faulting and eastward tilting of the sedimentary strata along the western margin of the Denver Basin occurred during the Laramide orogeny.

During the Paleocene, rhyodacitic sills and basaltic dikes were intruded into the sedimentary section in the Boulder area. Larson and Hoblitt (1973) report a radiometric age of 64.6 ± 2.4 m.y. on the Flagstaff mountain sill on the west side of the city and consider the east-northeast-trending Valmont dike on the east side of Boulder to be of similar age. The dike is 6–20 m (20–60 ft) wide, nearly vertical and has been traced, in the subsurface, for nearly 8 km (5 mi) with magnetic surveys (Colton, 1978).

During the Oligocene, the regional topography is thought to have been very similar to the present-day eastern plains of Colorado but with a maximum elevation of about 900 m (2,920 ft) (Trimble, 1980). This setting existed well into the Miocene when major thermal uplift and east-west extension began in central New Mexico and south-central Colorado and formed the Rio Grande Rift (Riecker, 1979). Late Miocene to present regional uplift involving much vertical movement on north-trending normal faults with attendant erosion has produced the Front Range that exists today west of Boulder (Epis et al., 1980). No Cenozoic sedimentary rocks are found in the Boulder area except for the thin Quaternary pediment gravels that blanket the eastern marginal areas of the Front Range.

Surficial Deposits

In the Boulder area, bedrock crops out at the surface or is locally covered by thin Quaternary surficial deposits. The Quaternary deposits are of seven main types: 1) glacial and periglacial deposits, 2) residual regolith, 3) pediment and terraced alluvium, 4) slope wash colluvium, 5) talus and landslide deposits, 6) valley fill alluvium and 7) eolian deposits (Wells, 1967; Wrucke and Wilson, 1967; and Madole, 1973). The mountainous western part of this area has been subject to continuous weathering and erosion since uplift began in Early Tertiary time, with the most recent episode of renewed uplift in the Pliocene or, possibly, continuing today (Scott, 1975). From the Continental Divide to about 16 km (10 mi) west of

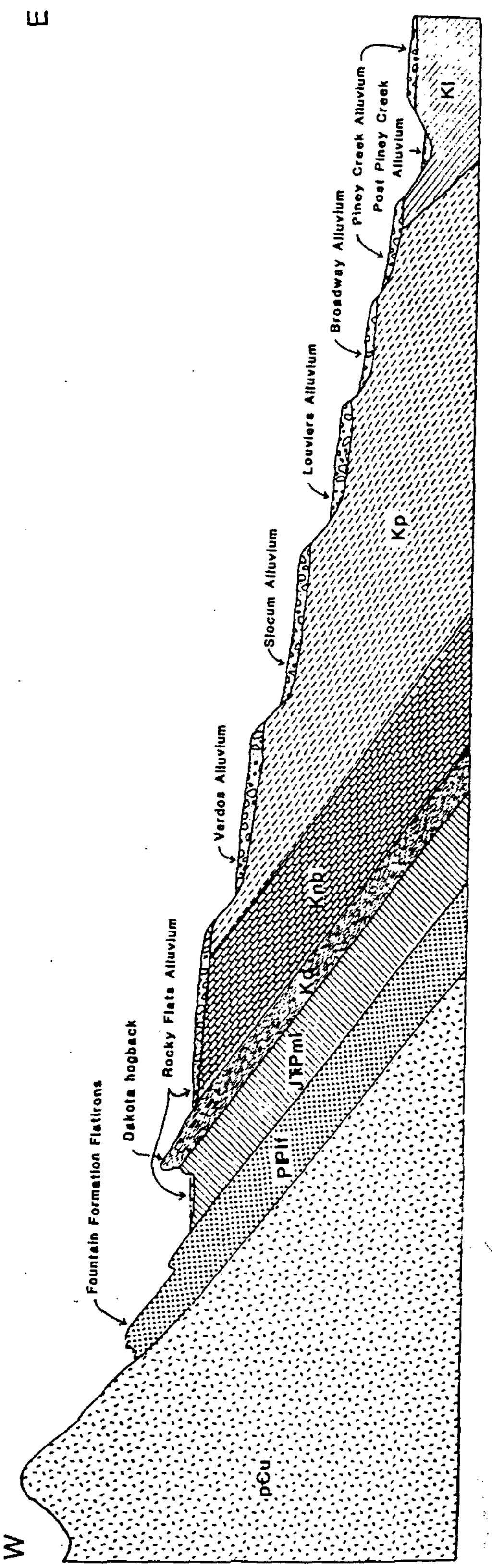


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Figure 8. Schematic cross section showing relative vertical relationships of the pediment and terraced alluvial units. Symbols as on Figure 3. Adapted from Scott (1963). Not to scale.

Boulder, glacial till and periglacial deposits such as talus, rock glaciers and solifluction lobes, are the main Quaternary units (Madole, 1973). Within the foothills area, a thin mantle of residual regolith overlying deeply weathered metamorphic or granitic bedrock is the dominant type of surficial deposit. In most upland areas, these deposits are only a few centimeters to 1–2 meters in thickness. This small thickness creates problems with respect to water supply and sewage treatment associated with housing development. In many areas, highly weathered Boulder Creek granodiorite is commonly treated as soil because it is easily excavated with a backhoe (Madole, 1973).

All of the pediment and terraced alluvium is of Pleistocene age and is generally divided into five different units: the Rocky Flats, Verdos, Slocum, Louviers and Broadway alluviums (Figures 5 and 8) (Scott, 1960). The first three are pediment gravels; and the last two are valley fill and terrace deposits restricted to present day stream drainages and involve no pediment cutting. These deposits have been correlated to geologic-climatic stages or cycles of Pleistocene glaciation in the higher Rocky Mountains to the west.

The Rocky Flats alluvium is the coarsest and most prominently displayed pediment alluvium in the Boulder area. An older, higher, but locally restricted "pre-Rocky Flats alluvium" is found just north of Coal Creek Canyon, about 13 km (8 mi) south of Boulder, but is not present within the city. From the southern margins of the city, the Rocky Flats alluvium continues southward along the mountain front for tens of kilometers, intermittently interrupted and dissected by major stream drainages. This alluvium is the remnant of an alluvial fan which has its apex at Coal Creek Canyon (Wells, 1967). Lithologically, the alluvium is composed of poorly sorted boulders, cobbles, pebbles and sand in a yellowish brown to red clayey matrix with layers of clay, silt, and sand and is 4.6–11 m (15–35 ft) thick. The grain size of the larger clasts decreases eastward away from the mountain front (Wells, 1967). Rocky Flats alluvium is of Nebraskan or Aftonian age, or about 1.0–2.0 m.y. old, and is about 91–105 m (300–345 ft) above modern stream levels (Scott, 1975; Trimble, 1975). In the southwestern part of the city, the Rocky Flats alluvium caps many of the wooded mesas that project eastward from the mountain front.

The Verdos alluvium (Scott, 1960) is the pediment alluvial deposit found 15–30 m (50–100 ft) below the Rocky Flats alluvium and 61–76 m (200–250 ft) above present streams. It consists of fairly well stratified brown sand and gravel (partly decomposed pebbles, cobbles and boulders of igneous, metamorphic and sedimentary rocks) in a clayey matrix (Wells, 1967; Wrucke and Wilson, 1967; and Trimble, 1975). The Verdos alluvium can be as thick as 10 m (33 ft) but averages about 4.6 m (15 ft). A locally diagnostic white, rhyolitic, volcanic ash bed near the base of the unit has been found at several localities in the region. This ash bed has been correlated by Scott (1960) with the Pearlette Ash Member of the Sappa Formation in Kansas and Nebraska, of Kansan or Yarmouth age or about 600,000 years old. The most extensive deposits occur as gravel-capped alluvial terraces or "mesas" along the Fourmile Canyon Creek drainage at the northern edge of the city and near the middle of town, where the Verdos underlies a major portion of the University of Colorado campus (Wrucke and Wilson, 1967).

The Slocum alluvium is the lowermost pediment alluvium in the area, occurring 15–30 m (50–100 ft) below the Verdos and about 24–40 m (80–130 ft) above present streams. The alluvium is generally similar to the Verdos in lithology and texture, but it is finer grained than the older alluviums (Scott, 1960; Wells, 1967; Trimble, 1975; and Costa and Bilodeau, 1982). The Slocum is generally less than 9 m (30 ft) thick, averaging 6–7 m (20–30 ft) and is considered to be of Illinoian age, or about 150,000 to 260,000 years old (Scott, 1960).

These three upper level pediment alluviums were all deposited by east-flowing streams on steam-cut bedrock surfaces, and all have well-developed soil profiles at their tops. The gravels in these deposits are commonly found coated and cemented with calcium carbonate, and they are oxidized reddish brown throughout, even where they are thick (Scott, 1960; Trimble, 1975). The deposits are thicker in paleochannels and thinner in interchannel areas, with the maximum size and roundness of the boulders and cobbles varying with the source stream and distance from the mountain front (Madole, 1973). Identification of the different alluvial terraces within a single drainage area is based primarily on relative topographic position, with the highest terrace always the oldest, reflecting continued uplift and base level lowering throughout Quaternary time.

The Louviers alluvium is a Late Pleistocene (Late Illinoian age-Bull Lake Glaciation, or about 140,000 years old (Pierce et al., 1976)) valley fill alluvium that is most often preserved below stream terraces

Gravels/cobbles mined at Sanitill

along present day east-flowing streams. It consists of slightly weathered, fairly well sorted and stratified, red to yellowish-brown sand, pebbles and cobbles in a clayey silt to sandy matrix. A strong, dark brown, clayey soil has developed at its top (Malde, 1955; Trimble, 1975). The alluvium is composed of two main facies, a coarser gravel facies present along major streams and a finer-grained silty facies that occurs along minor streams (Malde, 1955; Scott, 1960). The limited weathering of the gravel clasts in this unit has made it the major source of commercial sand and gravel in the Boulder-Denver region (Costa and Bilodeau, 1982). The Louviers alluvium has a highly variable thickness of 1–6 m (3–20 ft), occurs about 12–30 m (40–100 ft) below the Slocum alluvium and 6–20 m (20–65 ft) above modern streams (Malde, 1955; Scott, 1960; and Trimble, 1975). The depth of downcutting and base level lowering associated with the Louviers is the deepest of any of the Quaternary alluvial deposits (Scott, 1975; Trimble, 1975). Locally, along minor streams, post-Louviers erosion and downcutting has not cut entirely through the alluvium and modern streams are reworking the Louviers alluvium. Between Boulder Creek and South Boulder Creek, the Louviers alluvium underlies a thin layer of Broadway alluvium 61–183 cm (2–6 ft) thick (Trimble, 1975).

The Broadway alluvium is the lowest Pleistocene (Wisconsin age-Pinedale Glaciation, or about 30,000 years old (Pierce et al., 1976)) valley fill-terraced alluvium in the region (Scott, 1960). Lithologically, it consists of yellowish-orange to reddish brown, cobbly pebble gravel of predominantly Precambrian crystalline rock composition. A poorly developed brown soil is present at its top. The thickness of the alluvium is from 0–9 m (0–30 ft) underlying terraces 6–12 m (20–40 ft) above present streams (Trimble, 1975). To the southeast in the Denver area, the alluvium forms a broad, well-defined terrace upon which the largest and tallest buildings of downtown Denver have been built (Costa and Bilodeau, 1982).

Colluvium, talus and landslide deposits are locally very important but are usually restricted to fairly steep slopes or the bases of steep slopes or cliffs in the mountainous western part of the area. Landslide deposits are discussed in the Geologic Constraints section of this paper.

Valley fill alluvium is the term applied to the Holocene alluviums that fill the modern stream valleys of the area. Two alluvial deposits have been recognized, the Piney Creek alluvium and the post-Piney Creek alluvium (Malde, 1955). The Piney Creek alluvium is composed of brownish-gray silt, sand and clay with interstratified humic-rich layers. Close to the mountain front, gravel as coarse as small boulder size (36 cm or 14 in.) occurs in lenses near the base. The deposit forms terraces 1.2–6 m (4–20 ft) above modern streams and is from 0–6 m (0–20 ft) thick (Trimble, 1975). Carbon-14 dating establishes an approximate age of about 2,800 yrs (Scott, 1963). Post-Piney Creek alluvium consists of grayish-brown, humic, fine sand and silt, with loosely consolidated pebble and cobble lenses near the base. The alluvium is from 0.5–6 m (1.6–20 ft) thick, increases in thickness downstream, and covers almost the entire flood plain of the modern streams. Post-Piney Creek alluvium is primarily derived from Piney Creek alluvium and exhibits little or no soil development (Costa and Bilodeau, 1982). Carbon-14 dating places it at about 1,500 years old (Scott, 1963).

Eolian sand and silt (loess) of Holocene to Pleistocene (Sangamon) age is derived from the older Pleistocene alluviums and is the most extensive surficial deposit in the plains area east of Boulder (Colton, 1978; Trimble and Machette, 1979). This windblown deposit is 1–7.6 m (3–25 ft) thick and has a brown Holocene soil developed in its upper part (Trimble, 1975).

Seismicity

Colorado has, in general, been considered an area of low seismic activity. A few moderate earthquakes have caused damage over the past 110 years and hundreds of smaller earthquakes have been instrumentally recorded within the state (Figure 9). No surface fault ruptures have been detected in the state as a result of historic earthquake activity. Recent geological investigations, however, have discovered several faults that are considered "active" and capable of generating earthquakes. There are 5 faults within 80 km (50 mi) of Boulder which exhibit Quaternary (1.6 m.y. old) movement (Figure 10) (Kirkham and Rogers, 1981). The Valmont fault, which is less than 16 km (10 mi) from Boulder, offsets gravels within the Slocum alluvium (0.15–0.26 m.y. old). When evaluating the potential seismicity of this area, it is important to remember that the 4,300 m (14,000 ft) high mountains west of the city were uplifted in Neogene time and that the major uplifts occurred within the last 5 million years (Epis et al., 1980).

Concern about the potential seismicity of the Front Range area was raised in the 1960's when a series

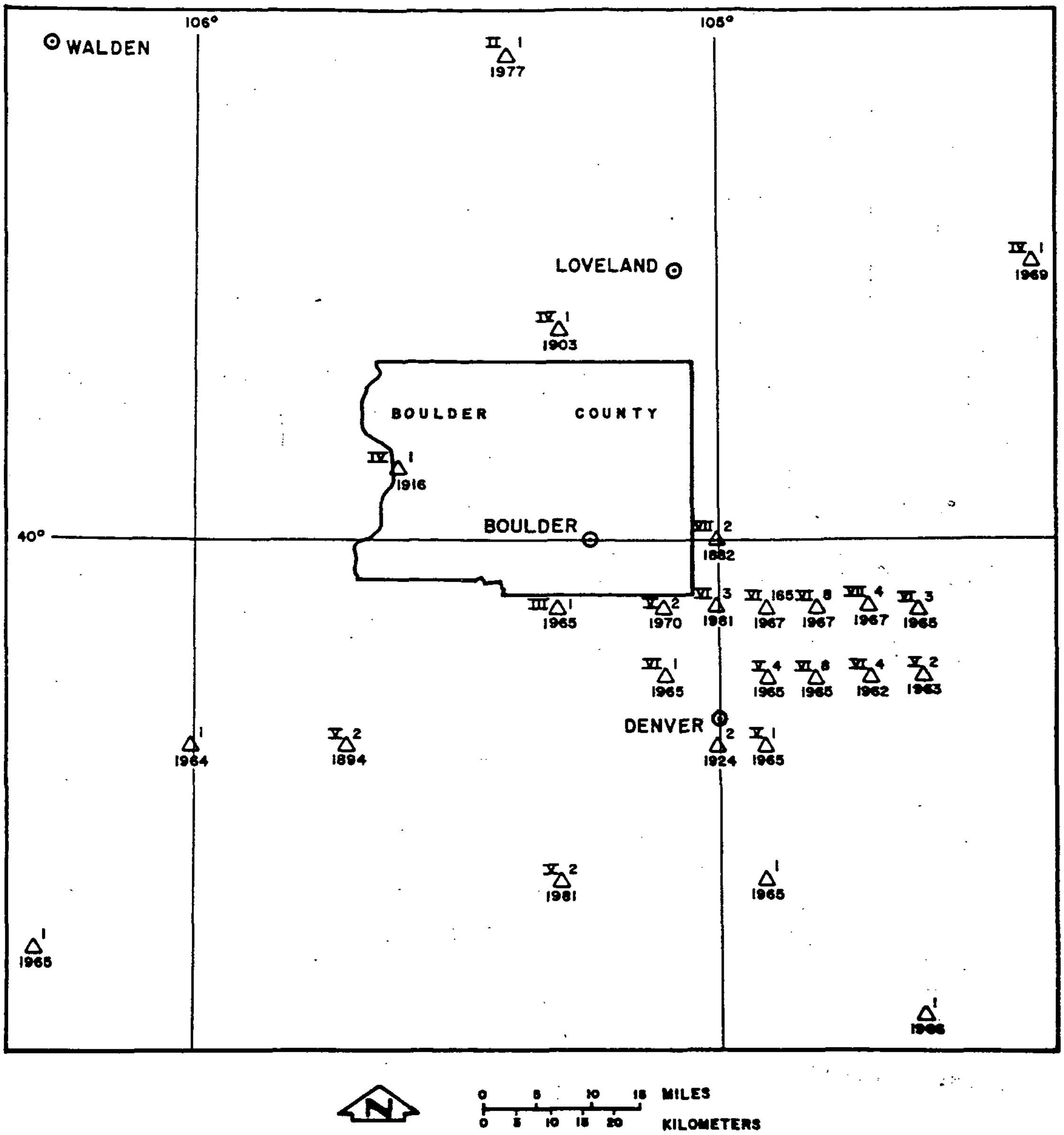

Figure 9. Earthquake epicenters and intensities in the Boulder area and vicinity 1882–1981. The triangles represent epicenters, the number of earthquakes at each location is shown by the number to the right of a triangle. The Roman numeral to the left of a triangle is the maximum Modified Mercalli intensity of all the earthquakes at that location. The number below a triangle is the latest year for which the maximum intensity was recorded. The 1882 earthquake epicenter is shown near Broomfield although other possible locations have been suggested (from Stover et al., 1984).

of earthquakes occurred in Denver, 45 km (28 mi) southeast of Boulder. The series lasted from 1962 to 1968, with the largest earthquake occurring in 1967 and measuring 5.3 on the Richter Scale (Kirkham and Rogers, 1981). The accompanying seismic shaking caused considerable damage in the surrounding suburbs, but Boulder was undamaged. Many geologists who have studied these earthquakes believe that a deep, high-pressure injection well, drilled by the U.S. Army at the Rocky Mountain Arsenal in northeast Denver, triggered the earthquakes (Evans, 1966; Healy et al., 1968). There is evidence that tectonic stresses existed in the area prior to the fluid injection because earthquakes continue to occur even though the well was decommissioned early in 1966 (Kirkham and Rogers, 1981).

The largest earthquake recorded in the area oc-

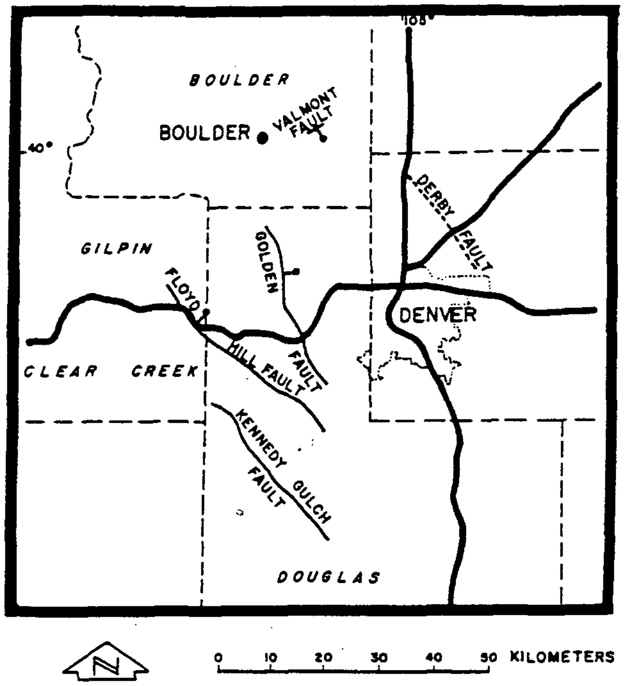

Figure 10. Map showing traces of known Quaternary faults in the Boulder area. Bar and ball are on the downthrown side. Dashed fault is deeply buried and inferred (from Hansen and Crosby, 1982).

curred in 1882. This earthquake caused Modified Mercali shaking of Intensity VII from Denver to Southern Wyoming (Epis et al., 1980). The walls of the Boulder County railroad depot cracked and plaster fell from walls at the University of Colorado. Early accounts of the earthquake suggest it was centered in the Broomfield-Louisville area (Figure 9); however, a Dames and Moore, Inc. (1981) study suggests that the epicenter may have been located in northwestern Colorado.

GEOTHECHNICAL CHARACTERISTICS

The geotechnical characteristics of the surficial and bedrock units in the Boulder area can change dramatically over very short distances. The following general descriptions provide typical conditions that can be expected for specific rock units. Many geologic constraints can be controlled through sound engineering design. On the other hand, areas affected by serious geologic constraints, such as subsidence over abandoned coal mines, are best avoided if possible.

Foundation Related Geologic Units

The valley fill and terraced alluviums consist of boulders, cobbles, gravel, sand, silt and clay. These deposits generally provide sufficient foundation support below a depth of about 0.7 m (2 ft). Locally, there are lenses of expansive clay and/or compressible silts present. These lenses average from 03.3–1.6 m (1–5 ft) thick and can cover as much as a few acres (Gardner, 1968). A caliche (hardpan) layer up to 1.6 m (5 ft) thick commonly is present within 1.0 m (3.3 ft) of the surface. Lenses of organic material 0.3–1.6 m (1–5 ft) thick may also be encountered. Settlement problems may be encountered when structures are constructed over compressible silts or organic-rich materials. Heaving problems may be encountered in areas of swelling clays. Mass movements can occur in valley fill and terraced alluviums. Areas of potential mass movement are generally restricted to hillslopes or along benches which have been undercut. Undercutting can be caused by natural erosion, such as fluvial action or human-induced causes, such as construction. These deposits are generally easy to excavate.

The Arapahoe Formation covers less than 9 km^2 (3.5 mi^2) in the southeast corner of Boulder County. It is composed of conglomerate, sandstone, shale and claystone. Generally, this formation provides adequate bearing strength for most structures. The claystone, however, is often expansive and can swell if moisture is introduced. Shale and claystone are usually easy to excavate, while conglomerate and sandstone may require ripping if they are cemented.

The Laramie Formation consists of interbedded shale, siltstone and sandstone that contain lenses of coal and clay. Locally, the formation is faulted and fractured. The coal in this formation was extensively mined in southeastern Boulder County and subsidence over abandoned mines is a continuing problem. Slope stability is generally good in unsaturated slopes of less than 25°. Numerous slope failures have occurred in the southern portion of the county where slopes exceed 25° and where bedding surfaces or clay seams dip in the same direction as the hillslope but at a smaller angle relative to the slope (Figure 11). Foundation suitability of this formation is generally good where expansive clay, slope stability and subsidence problems are absent. Excavation of the shale and siltstone beds is relatively easy using conventional methods. Excavation of the sandstone beds is moderately difficult.

The Fox Hills Sandstone is composed predominantly of sandstone and siltstone, which vary from unconsolidated to very hard. This formation generally has high bearing strength. Excavation of the siltstone beds is relatively easy, but where cemented

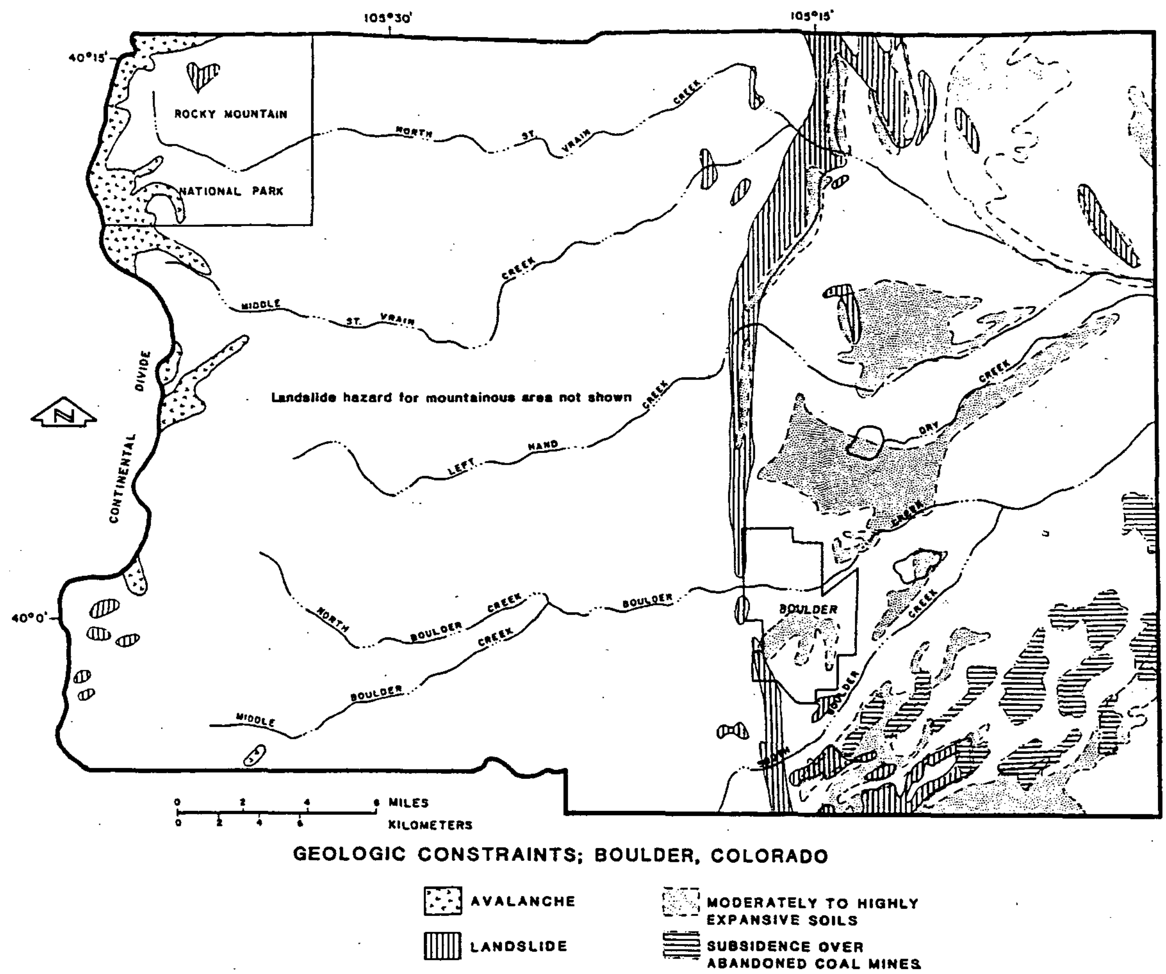

Figure 11. Geologic constraints map, Boulder County. Modified from Madole (1973), Hart (1974), and Boulder County Planning Commission (1978).

sandstone beds are encountered, blasting may be required for foundation excavations.

The Pierre Shale consists of 2,300 m (7,546 ft) of shale with thin layers of bentonite, siltstone and sandstone. The strike of the formation if roughly north-south and the dip is nearly vertical adjacent to the mountain front. The dip flattens to 25° where the formation crops out on the eastern side of town. This formation underlies the majority of the urbanized area and exhibits moderately to highly expansive characteristics over approximately ⅓ of its outcrop area (Figures 3 and 11). Soils which form from the weathering of Pierre Shale typically exhibit some swelling. Swell pressures ranging from 3.0–6.0 GPa (3,000–6,000 psf) are not unusual. The foundation suitability of the Pierre Shale depends on building load, foundation design and change in moisture content after construction. The Pierre Shale generally exhibits a low shear strength. Much of the formation will expand moderately and exert moderate swelling pressures if the moisture content increases. Slope stability is fair to good where slopes are undisturbed or where bedding dips into the slope. Locally, slope stability can be poor for steep cuts exceeding 6 m (20 ft) in height and for cuts where bedding dips in the same direction as the hillslope but at a smaller angle relative to the slope, especially if a bentonite or clay layer is present. If these conditions are present, the Pierre Shale can exhibit progressive slope failure which migrates headward and can be difficult to arrest. Excavation is generally possible to depths of 4.6 m (15 ft) with most available construction equipment. If excavations are left open, slaking of the formation is common.

The remaining sedimentary rock formations are present only as narrow outcrop bands paralleling

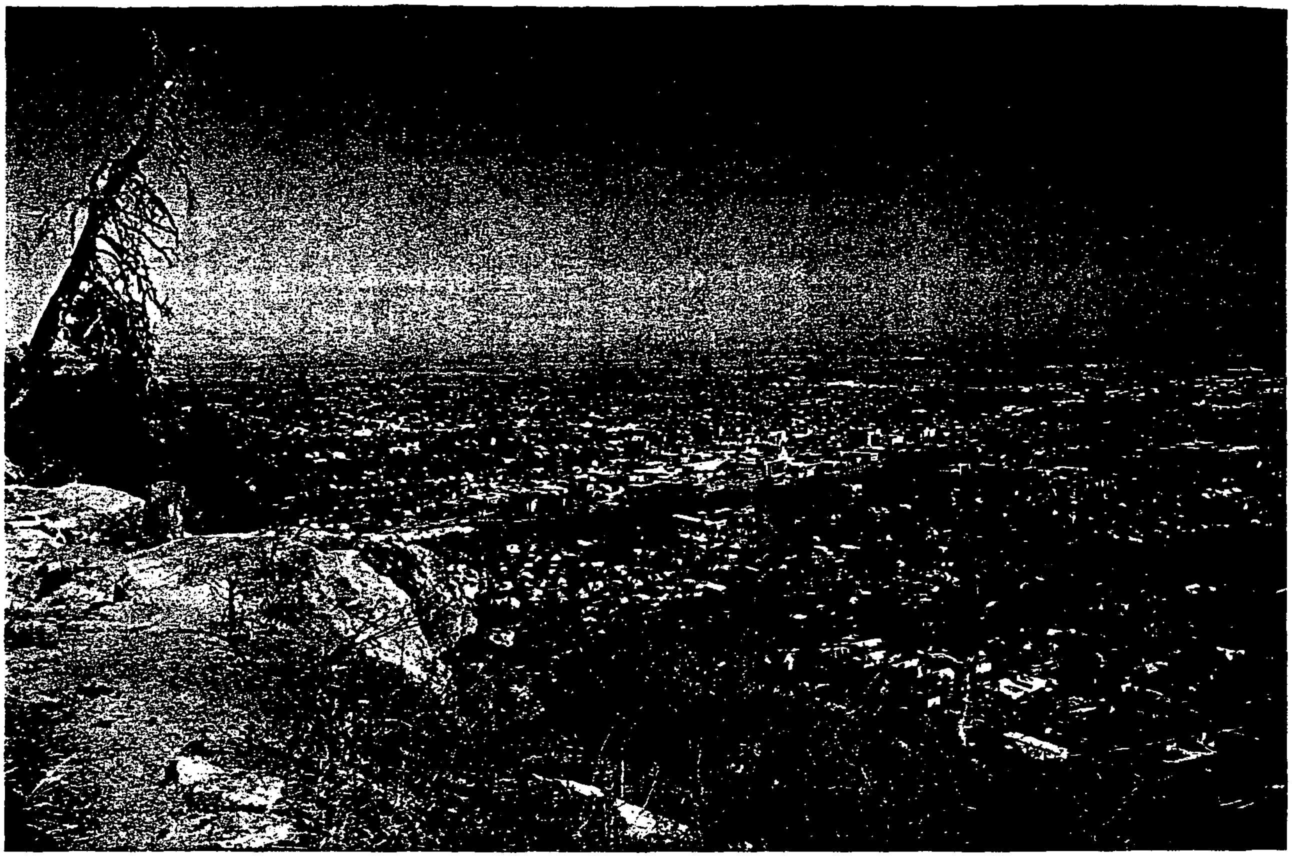

Figure 12. View of Boulder looking east from Flagstaff Mountain.

the mountain front (Figure 3). Most of these formations present few foundation problems. Due to their steeply dipping bedding attitudes, landslides and rockfalls locally present problems where the formations are undercut or where dip slope conditions exist. Some claystones and shales present in this area exhibit moderate to high swell potential.

Crystalline rocks are present in the sparsely developed, western mountainous portion of Boulder County. Few foundation problems are present in this area, with the exception of slope stability. There is a moderate risk from rockfalls and small debris slides along the steep slopes of valleys.

Exploration and Testing Methods

When conducting geotechnical exploration of specific sites within Boulder County, the first step is generally to review available technical literature. There are numerous geologic and soil reports which cover the county area, and several quadrangles have been mapped by the U.S. Geological Survey at 1:24,000 scale. These maps cover a range of topics of interest, including bedrock geology, surficial deposits, and engineering properties (Malde, 1955; Wells, 1967; Wrucke and Wilson, 1967; Gardner, 1968, 1969; and Trimble, 1975). The Soil Conservation Service has also published a soil survey of Boulder County (Moreland and Moreland, 1975).

Subsurface exploration for engineering geological purposes is accomplished through the opening of trenches or boreholes. Trenches are generally opened to a depth of 3 m (10 ft) with tire or track-mounted backhoes. Borings are drilled with continuous flight augers, hollow stem augers or rotary wash drilling rigs. Samples are obtained with the Standard Split Spoon, Shelby Tubes or California (Ring) Samplers. Standard penetration tests are commonly used to determine *in-situ* consistency of soil and weathered rock materials. Rock core drilling is used where bedrock information is needed.

The most common laboratory tests performed include: Atterberg limits, grain size distribution, moisture content and dry density, direct shear, and one dimensional consolidation-swell tests. Tests are

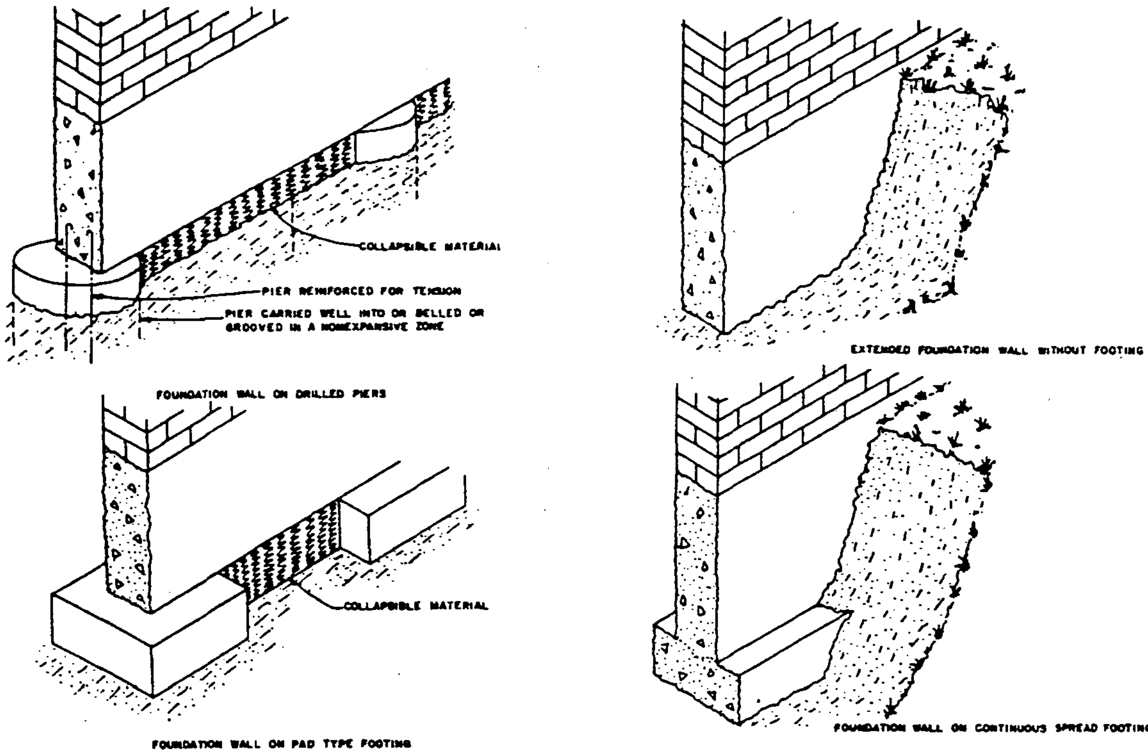

Figure 13. Typical foundations in use in Boulder County (from Holtz and Hart, 1978).

generally performed to published reproducible standards such as the American Society for Testing and Materials (ASTM) or other soil testing laboratory manuals or standards.

Typical Foundation Types in Use

The City of Boulder limits the height of buildings to 16.8 m (55 ft). This ordinance was enacted to preserve the spectacular mountain view from the downtown area as well as to maintain a small-town atmosphere (Figure 12). In Boulder County, similar ordinances restrict building heights in residential areas to 10.7 m (35 ft) and buildings in industrial and agricultural areas to 15.2 m (50 ft). These restrictions limit the variety of foundation types needed in the area. Typical foundations used are continuous spread footings, pads with grade beams, wall-on-grade, or drilled piers (caissons) with grade beams (Figure 13).

Much of the downtown area is underlain by river sand and gravel with bearing capacities of 4.0–6.0 GPa (4,000 to 6,000 psf). Most of the buildings in this area have continuous spread footing type foundations. Although most of the footings are constructed of concrete, there are some in older structures that are constructed of Lyons Sandstone slabs stacked upon each other and mortared together (Nasiatka, 1984). Where the ground-water level is high some river sands will flow into open excavations. This can undermine adjacent structural foundations. Driving steel sheet piling along the proposed excavation has proven effective. When the Exeter Building, at 1050 Walnut Street, was under construction, the adjacent building had to be underpinned to prevent foundation distress.

In areas where expansive soil has been identified, certain methods of design, construction, and maintenance have been used to avoid structural damage. Where soils have moderate to high expansion potential, drilled pier and grade beam foundations are typically used. This method of foundation design is typical of the Front Range area. The drilled piers are extended below the zone of seasonal moisture change and are designed so that foundation loads are concentrated to withstand uplift pressures from expansive soils. The grade beams are constructed so that a 7.6–15.2 cm (3–6 in.) space exists between the expansive soil and the bottom of the beam. This allows the soils adjacent to and beneath the foundation to expand without generating uplift pressures against the base of the grade beams (Figure 13). When drilling the holes for the piers, care must be taken to prevent enlargement of the top of the hole. If the top of the drill hole is enlarged and no forms are used to prevent the concrete from filling the void, the result is a mushroom-topped drilled pier. Expansive pressures have been known to break or lift mushroom-topped drilled piers out of the ground.

Where soils have moderate to low expansion potential, pads with grade beams and/or wall-on-grade foundations are often used. These foundation systems are similar to the drilled pier and grade beam foundation in that they are designed to concentrate structural loads sufficiently to resist uplift pressures resulting from soil expansion.

In most instances, continuous spread footings are generally not recommended for areas with swell potential. In contrast to the foundation systems described above, continuous spread footing foundations distribute structural loads and are therefore less suited to withstand pressures generated by soil uplift.

A segmented interior design is generally recommended in structures founded on expansive soil. Most ground or basement floor slabs constructed on expansive soils are "floating." That is, they are generally designed with a joint separating the slab from the structural or load bearing walls. If the interior non-load bearing walls are tightly attached to the slab, the upward movement can cause interior damage.

Positive drainage away from the foundation is another important aspect of building on expansive soils. Hart (1974) recommends 30 cm (12 in.) of vertical fall in 3 m (10 ft) around the building. All downspouts and splash blocks should allow roof runoff to be discharged at least 1.2 m (4 ft) away from the building. In areas of heavy lawn watering, properly directed peripheral drain pipes are effective in helping to prevent water from collecting around the foundation. Grass, shrubs, and sprinkler systems should also be kept a minimum of 1.2 m (4 ft) away from the foundation. Trees should be planted no closer than 4.6 m (15 ft) from foundations.

Construction problems related to swelling soils commonly include mushroom-topped drilled piers, lack of adequate expansion void space between soils and grade beams, allowing clays to dry excessively before pouring concrete, allowing water to pond near the foundation during construction, building without allowance for basement or ground floor movement, and improper landscaping and surface drainage (Shelton and Prouty, 1979).

ECONOMIC DEPOSITS

The Colorado Division of Mines formerly published an annual summary of mineral industry activities (Colorado Division of Mines, 1980). This practice was curtailed after 1980, hence the latest readily available information regarding production and sales of minerals in Boulder County is from this 1980 publication.

Sand and Gravel

Sand and gravel deposits of economic value in Boulder County are located primarily within the physiographic flood plains of South Boulder, Boulder, and St. Vrain creeks (Figure 14; Schwochow et al., 1974). These deposits occur within the Louviers, Broadway and Piney Creek alluviums and are the prime commercial mineral deposits in the county, in both volume and value. An inventory of these deposits shows that out of an original estimated inventory of 446,024,000 metric tonnes (439,000,000 tons), 12 percent or 54,864,000 metric tonnes (54,000,000 tons) have been extracted to date, 52 percent or 231,648,000 metric tonnes (228,000,000 tons) remain technically available for extraction, and 36 percent or 159,512,000 metric tonnes (157,000,000 tons) have been lost for extraction due to urban development (Boulder County Planning Commission, 1984).

Sand and gravel are used mainly in the production of concrete aggregate, for use on construction and paving projects. A large amount is also consumed in the production of asphaltic concrete. Because sand and gravel have a low unit value, they cannot be hauled far and remain a profitable commodity. In 1980, the dollar value of sand and gravel mined in Boulder County was over $5,500,000 (Colorado Division of Mines, 1980).

The City of Boulder and Boulder County have developed comprehensive planning programs for the extraction of sand and gravel materials. This was in direct response to the Colorado Legislature House Bill 1529, which was enacted in 1973 to prevent land uses that could prohibit extraction of valuable sand and gravel resources in the area. Because most of Boulder's high quality gravel deposits are located in flood plains, extraction pits often extend below the ground-water level. Portions of one area of extensive mining, Sawhill Ponds, in the Boulder Creek flood plain, have been reclaimed and converted into Walden Ponds Wildlife Habitat (Figure 15). Active

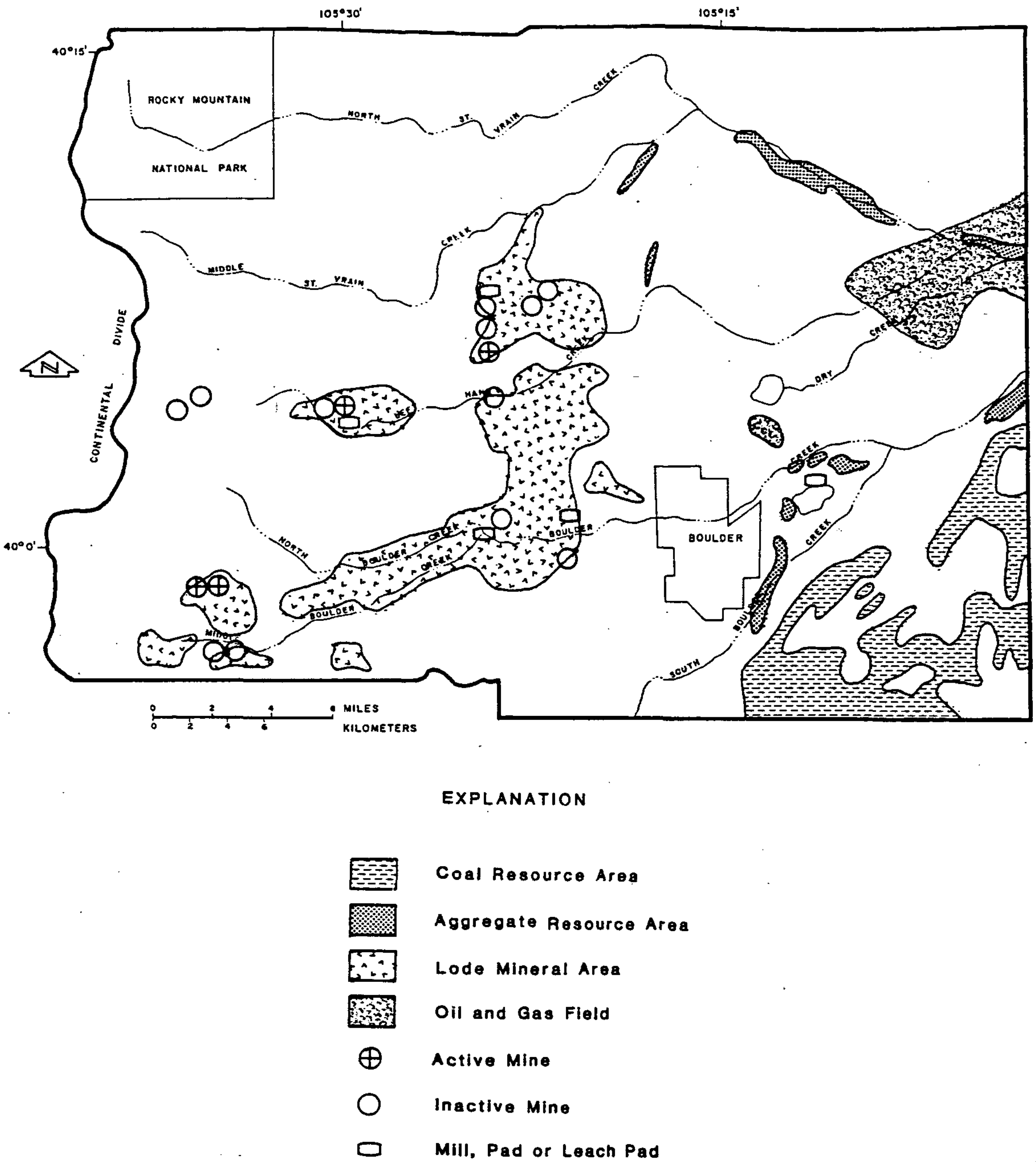

Figure 14. Map showing mineral and fuel resource areas and mining operations. Adapted from Boulder County Planning Commission (1978) and Hornbaker (1984).

mining is continuing today on the margins of these reclaimed, water-filled extraction pits.

Clay Minerals

Eastern Boulder County has some reserves of clay minerals suitable for production of brick, tile, blocks, pipe, and culverts. Good quality refractory clays are limited to the South Platte Formation of the Cretaceous Dakota Group in the south-central part of the county (Madole, 1973). Amost all clay produced in Boulder County comes from the El Dorado Springs-Superior-Marshall area (Figure 1). A limited amount of clay is mined near manufacturing sites, where it is used as an additive or supplement

Figure 15. Sand and gravel operations adjacent to Walden Ponds Wildlife Habitat; location 9 on Figure 1.

to clay that is imported. The Lykins, Morrison, and Benton formations contain clays that can be used in this manner. In 1980, over $25,000 worth of clay was mined in the county (Colorado Division of Mines, 1980).

Limestone and Cement

Limestone is currently being mined 18 km (11 mi) north of Boulder by the Martin Marietta Corporation (Figure 1). The Fort Hayes Limestone Member of the Upper Cretaceous Niobrara Formation is the principal source. Cement is produced in just three plants in Colorado; the Martin Marietta plant north of Boulder is one of them (Figure 16). In 1980, the dollar value of cement produced in Boulder County was approximately $14,000,000 (Colorado Division of Mines, 1980).

Fluorspar

Fluorspar is mined by Allied Chemical Company in the Jamestown mining district, west of Boulder. Fluorspar is essential in the chemical, steel, aluminum, and ceramic industries. In the U.S., it is presently the only commercially developed source of the element fluorine from which hydrofluoric acid and fluoride compounds are manufactured (Madole, 1973).

Stone

Building stone in Boulder is derived almost exclusively from the Permian Lyons Sandstone near the City of Lyons, 20 km (12 mi) to the north, where the formation is well exposed and accessible to heavy equipment. Many of the older buildings around town are constructed almost entirely of this eolian "flagstone." Nearly $450,000 worth of stone was mined in Boulder County in 1980 (Colorado Division of Mines, 1980). Several old sandstone quarries are located along the mountain front in the southwestern part of Boulder.

Silica Sand

Silica sand has been mined locally in Boulder County for use in the manufacture of cement and

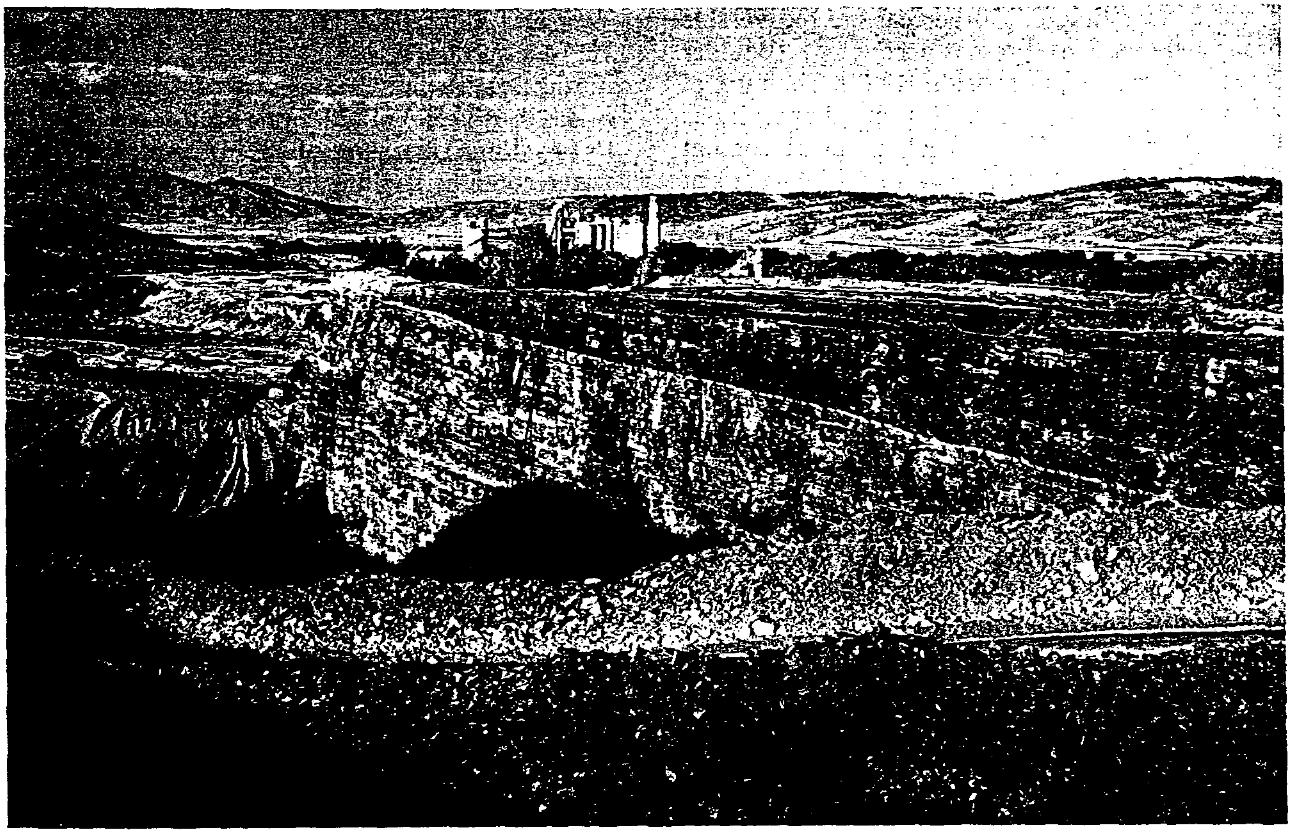

Figure 16. Martin Marietta cement plant in background, limestone quarry in Fort Hays Limestone member of the Niobrara Formation *in the foreground; location* 1 on Figure 1.

clay products. The principal source is sandstone in the Cretaceous Dakota Group. Martin Marietta Corporation is the major local consumer of silica sand.

Coal

Coal of economic importance occurs principally in the Boulder-Weld Coal Field southeast of Boulder (Figure 14). The Upper Cretaceous Laramie Formation is the principal coal-bearing unit. Three main coal beds were mined from the lower 38 m (125 ft) of the formation. The coal beds range in thickness from a wedge-edge to 12 m (40 ft) (Spencer, 1961). The coals were deposited in a delta plain depositional environment and are locally associated with a major northeast-trending fault zone 16.6 km (10 mi) wide and 50 km (30 mi) long, named the Boulder-Weld fault zone by Davis and Weimer (1976) (Figure 3). The horsts and grabens that were formed in the complex system of faults controlled the deposition of the coals as they are thickest in the grabens and thin over the horsts. Seismic reflection data suggest that these are aseismic synsedimentary growth faults related to the deltaic sedimentation which was, in turn, localized by Late Cretaceous movement on basement faults (Davis and Weimer, 1976).

Coal mining began as early as 1863 near Marshall. This area is one of the oldest coal mining areas in the Western United States (Kirkham and Ladwig, 1979). Most early mines consisted of adits dug into coal seams that were exposed at the surface; a few were open pit mines, with most of the remainder being underground room and pillar mines. Some areas above abandoned coal mines are experiencing subsidence (discussed in the Geologic Constraints section). Coal mining in the Boulder-Weld Field peaked in 1929. Production and mining activity has gradually decreased since that year and no coal mines are known to be active since 1976 (Kirkham and Ladwig, 1979; Bryan, 1984). Original reserves were estimated at 472,582,240 metric tonnes (465,140,000 tons). Remaining reserves are approximated at 384,393 metric tonnes (378,340 tons) of which an estimated 50 percent are recoverable through the use of present technology (Boulder County Planning Commission, 1978). The rank of coal in Boulder County ranges from subbituminous A to subbituminous B. The coal has an ash content of about 7.3 percent, a sulfur content of 0.4 percent and contains about 12,280 BTU's per pound (Boulder County Planning Commission, 1978). A study conducted in 1978 suggested that coal could not be extracted for less than 133 percent of the market price, excluding transportation costs (Pendleton, 1978).

Loam and Peat

Peat and loam have been mined commercially at Beaver Reservoir, Lefthand Reservoir, and Brainard Lake (Madole, 1973). The net dollar value of loam and peat mined from 1952 to 1971 amounted to $320,054. Peat reserves are limited to westernmost Boulder County. Although they have not been estimated officially, the reserves are considered substantial.

Oil and Gas

Petroleum has been produced in Boulder County since 1901, when the Boulder Field was discovered. Other fields have been discovered since then, although the area has never become a significant petroleum producer (Figure 14). Production from the Codell Sandstone, Hygiene Sandstone Member of the Pierre Shale, fractured zones in the Pierre Shale, and sandstones of the Dakota Group has increased since the prices of oil and gas skyrocketed in the 1970's. Discovery of the Boulder Valley Field about 11 km (6 mi) east-northeast of Boulder in 1979, which produces from the Codell Sandstone, is considered to have been the catalyst that sparked the current Codell play in the Denver Basin (Petroleum Information, 1983). Production from the Boulder Valley field began in 1981 when the wells were connected to pipeline. In December 1980, there were 10 producing wells filed within the county, accounting for nearly 7,000 Bls of oil and 70,000 Mcf of gas (Colorado Oil and Gas Conservation Commission, 1980). The dollar value of the oil and gas produced was approximately $250,000 (Colorado Division of Mines, 1980).

Geothermal Resources

In the vicinity of Boulder, two areas have been identified which possess warm water resulting from geothermal activity: the Haystack Butte Warm Water Well and Eldorado Warm Springs (Figure 1). The Haystack Butte Warm Water Well, located to the northeast of Boulder, is an unused oil test well drilled in 1920. It is 894 m (2,932 ft) deep and has a 0.25 l/s (4 gal/min) discharge of 28°C (82.4°F) water. The water contains sodium bicarbonate with approximately 1,200 mg/l total dissolved solids. Attempts to plug the well were unsuccessful, and the seeping water was used for a wading pool in the 1920's and 1930's and later as a baptismal font by a religious group. At present, the water is used in a swimming pool and to water game birds (Barrett and Pearl, 1978).

Geologically, the well is located on the crest of a southward plunging faulted anticline (old Boulder Oil Field). The heat source for the geothermal water is probably associated with the emplacement of the Tertiary igneous rocks described in previous sections of this paper (Barrett and Pearl, 1978). This anticlinal geothermal reservoir is approximately 1.4 to 4 km^2 (0.54 to 1.54 mi^2) in size.

Eldorado Warm Springs, located about 13 km (8 mi) south of Boulder, along South Boulder Creek, contains natural springs and drilled wells. The springs and wells are used to warm a swimming pool which has been the central attraction for a popular resort since the late 1800's. Water from the spring has also been bottled and sold commercially. The temperature of the warm water varies annually from 24°C to 26°C (75°F–79°F) and contains calcium sulfate. Total dissolved solids range from 84–101 mg/l (Barrett and Pearl, 1978).

Geologically, the warm water flows from springs in the South Boulder Creek alluvium, which overlies steeply dipping sandstones of the Fountain and Lyons formations. The mechanism for heating has been attributed to circulation through faults and fractures in the igneous and metamorphic basement complex to the west of Eldorado Springs (Barrett and Pearl, 1978). The geothermal reservoir extends west of the springs and covers an area of approximately 129.5 km^2 (50 mi^2).

Metallic Minerals

Metallic minerals have been mined in western Boulder County since 1859, when gold was discovered at Gold Hill. Six districts have been established: the Central (Jamestown), Gold Hill (Salina, Rowena, and Sunshine), Magnolia, Sugarloaf, Ward, and Grand Island (Cardinal, Carbon, Eldora, and Nederland) (Figure 14). The metals produced include gold, silver, tungsten, copper, lead, zinc, tin, and uranium (Madole, 1973). The dollar value of gold, silver and tungsten mined was nearly $330,000 in 1980 (Colorado Division of Mines, 1980).

GEOLOGIC CONSTRAINTS

Expansive Soil

Expansive soil is one of the most prevalent and costly geologic problems in Colorado. Swelling soil damage to public facilities in Colorado costs approximately $16,000,000 annually (Shelton and Prouty, 1979). The problem with swelling soils in Colorado is so severe, in fact, that the Homeowners Warranty (HOW) Insurance Program suggested in 1980 that over 50 to 70 percent of its claims occurred in the Front Range region as a direct result of moisture sensitive soils (Lord, 1980).

In the Boulder area, swelling soil is the result of the inherent clay mineralogy. Soils derived from parts of the Laramie Formation and the Pierre Shale commonly contain montmorillonite and other smectite clay minerals. The crystal structure of these clay minerals allow them to absorb water between atomic lattice layers. As a result, these minerals increase in volume when wetted, and shrink when dried. A sample of pure montmorillonite can swell up to 2,000 percent of its original volume; however, most natural soils rarely swell more than 50 percent of their original volume (Hansen and Crosby, 1982; Hart, 1974). Expansive forces are capable of exerting pressures of 19.9 GPa (20,000 psf) or greater on confining structures such as foundations (Shelton and Prouty, 1979). Swell pressures of 4.0 GPa (4,000 psf) are very common in areas of Boulder County where montmorillonitic soils exist. The ultimate volume change of a soil sample is dependent on the percentage of smectite clay minerals present, existing moisture content, soil permeability, soil density, past strain history, extent of seasonal wetting and drying, and confining pressures (Hansen and Crosby, 1982).

Swelling soil conditions in Boulder represent the most widespread geologic constraint for development (Figure 11). Differential movement resulting from expansive soils has caused structural damage to many buildings in Boulder County (Figure 17). To reduce the potential for structural distress, common construction practice is directed towards either minimizing the potential for moisture variations which cause soil expansion or using foundation systems capable of withstanding or avoiding soil movement. According to Holtz and Hart (1978), damaging soil moisture variations can occur due to: 1) boundary effects of wetting or drying on a covered area, 2) seasonal or cyclic weather changes, 3) drainage problems, 4) landscape watering and 5) removal of soil moisture through evapotranspiration by local vegetation.

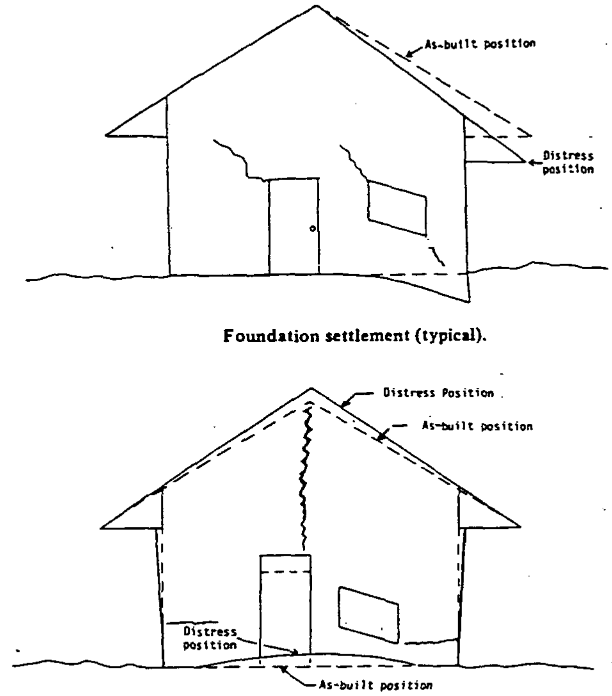

Figure 17. Typical damage to buildings caused by expansive soils in Boulder County (from Shelton and Prouty, 1979).

argument for xeroscape gardens!

Five construction techniques are generally effective in areas of expansive soils: 1) remove the soil and replace it with nonswelling material, 2) place foundation elements below the zone of seasonal moisture change, 3) install impermeable barriers to minimize soil moisture changes adjacent to and beneath the structure, 4) chemically treat the soil to inhibit swelling and 5) concentrate foundation loads sufficiently to withstand uplift pressures. Methods for testing for expansive soils and a more detailed description of typical foundations used in areas of expansive soils are described later in this paper.

Floods

Since 1864, Boulder has experienced 5 major flood events from Boulder Creek. All of the floods have occurred in May or June, when snowmelt is augmented by intense rainstorms. During May 21–23, 1876, a general storm over the Boulder Creek basin

Figure 18. Large boulder in Boulder Creek located on the edge of the city; location 5 on Figure 1. Note car license plate for scale.

created flooding on the plains reportedly 2.4 km (1.5 mi) wide. Railroad service was disrupted and fences and bridges were swept away (Muller Engineering Company, Inc., 1983).

The greatest flood known in Boulder occurred on May 30, 1894, when 11.4–15.2 cm (4.5 to 6.0 in.) of precipitation fell in the Boulder Creek drainage area. Buildings, bridges, roads and railroads were washed away. Floodwaters covered the entire area from Canyon Boulevard to University Hill to depths as great as 2.4 m (8 ft). In the valley downstream from Boulder, the flood plain was reported to have been inundated to an average width of approximately 1.6 km (1 mi) for several days (Muller Engineering Company, Inc., 1983). The other major floods occurred in June 1914, June 1921, and May 1969. Evidence for the magnitude of maximum flow during floods is dramatically illustrated by the size of rounded boulders located in Boulder Creek at the mouth of Boulder Canyon (Figure 18). Analysis of the coarsest 25 percent of Boulder Creek's flood-plain alluvium near the mouth of the creek gives a mean intermediate diameter of 188 cm (6.2 ft) for these boulders. A flow of about 625 m^3/s (22,000 ft^3/s), with a velocity of 4.6 to 6.1 m/s (15 to 20 ft/s), and a depth of 3.4 to 4.9 m (11 to 16 ft) is needed to move boulders of this size in Boulder Creek (Bradley and Mears, 1980).

As early as 1969 Boulder had adopted a zoning resolution that regulated land-use practices within the 100-yr flood plain (Taylor, Alan 1984). Much of the flood planning in the foothills was reviewed after the 1976 Big Thompson flood which occurred north of Boulder. This unprecedented event was caused by a very intense rainstorm which was unusually stationary and concentrated its rainfall over one drainage basin. In 1977, the U.S. Army Corps of Engineers estimated that a 100-yr flood could result in $22 million (in 1977 dollars) in losses in the Boulder area (Pendleton, 1978).

In 1983, Boulder County, the City of Boulder and the Colorado Water Conservation Board contracted the Muller Engineering Company to review and update the flood hazard areas for Boulder Creek. The

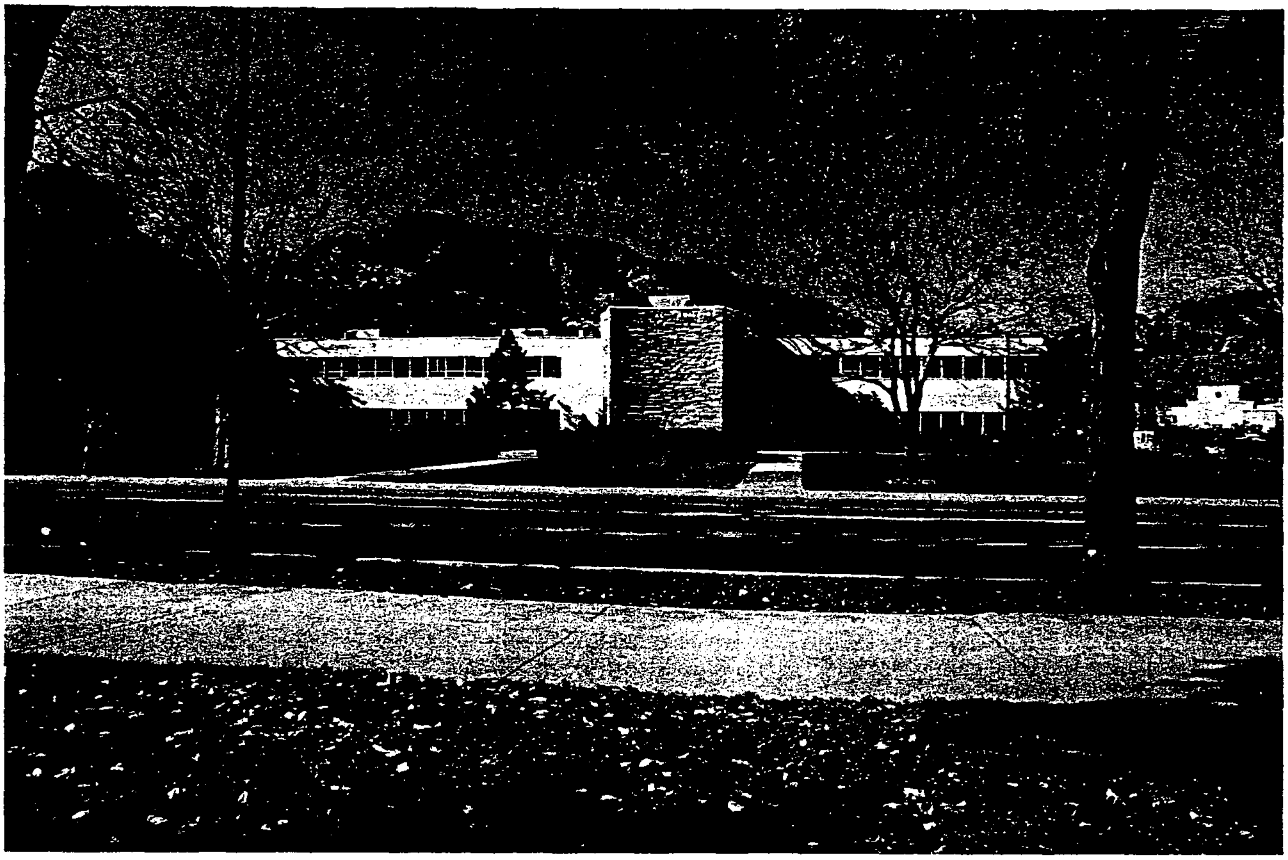

Figure 19. City of Boulder municipal building sited on the Boulder Creek flood plain less than 200 ft from the creek; location 6 on Figure 1.

resulting maps have a more accurate delimitation of the flood plain. These maps are used for planning and insurance purposes. It is interesting to note that the city's Municipal Building and Park Central Building, where the planning department resides, are located on the banks of Boulder Creek and are within the floodway of the creek (Figure 19). According to Alan Taylor (1984), the buildings were erected in the 1950's, prior to the city's flood-plain planning. The Columbia Savings building at 28th Street and Arapahoe Avenue was designed and built to withstand expected floodwaters (Figure 20). It was, however, one of the most expensive one story structures to be erected in the area.

Hydrocompaction

The major hydrocompaction problems in the Boulder area occur in soils composed of loess. Collapse-prone soils predominantly consist of silt and clay sized particles that were wind deposited in sheltered areas during glacial and interglacial periods. Typically, these deposits have a low density. Although they demonstrate high bearing strength when dry, they lose much of their strength when saturated and settle or collapse. Activities such as irrigation or lawn watering can trigger a collapse. Volume reductions are typically 10 to 15 percent (Shelton and Prouty, 1979). Surface ground displacement of up to a meter (3.3 ft) can result. Loess deposits up to 3.7 m (12 ft) thick have been discovered in downtown Boulder through subsurface exploration (Pendleton, 1978). Loess is also particularly vulnerable to wind or water erosion when stripped of its vegetative cover. Three construction techniques are generally effective in areas of collapsible soils: 1) remove the soil or place foundation elements below it, 2) prevent wetting of the soils adjacent to and beneath the structure, or 3) pre-collapse the soils prior to construction (Shelton and Prouty, 1979).

Mass Movements

Landslides, debris flows and rock falls are part of the natural erosive process. These processes are particularly active in areas of moderate to high relief

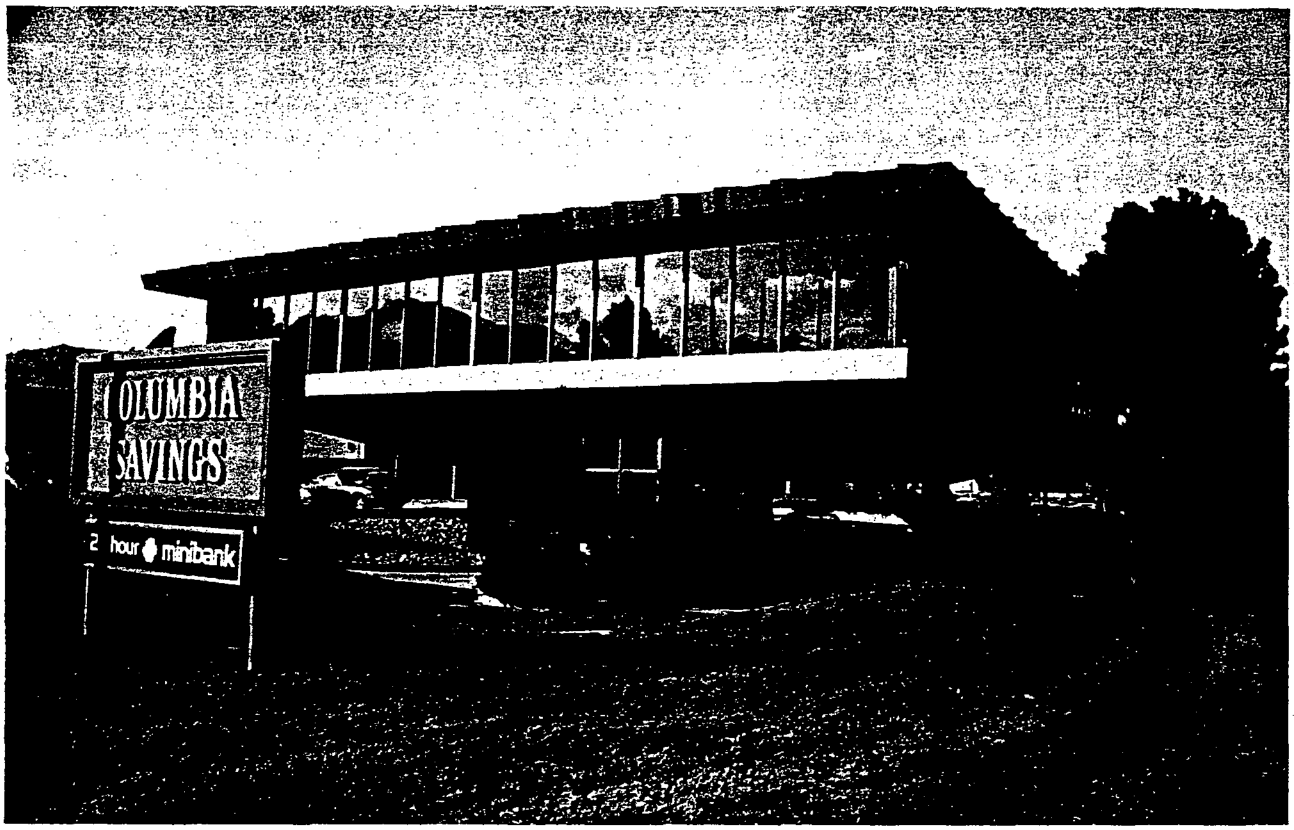

Figure 20. The Columbia Savings building, located on the flood plain of Boulder Creek, was designed with potential flood hazards in mind; location 7 on Figure 1.

which are underlain by sedimentary rocks typical of the Boulder area. Four geologic units are particularly susceptible to landsliding: the Lykins Formation, the upper part of the Dakota Group, and the weathered shale of the Laramie and Pierre formations.

The Lykins Formation underlies the strike valley between the hogbacks formed by the Lyons Sandstone and the Dakota Group. The biggest landslide problems occur on the west side of the valley where the permeable Lyons Sandstone discharges water along the dip slope into the Lykins Formation, causing many small landslides to occur.

The landslides in the upper part of the Dakota Group are found along the dip slope of the Dakota hogback. These landslides are considerably older than those present in the Lykins Formation and generally lack evidence for recent movement. These slope failures may have resulted from a time when the climate was wetter.

The Pierre Shale and the Laramie Formation provide the most significant landslide hazard to urban development because of their large outcrop area (Figure 3). Both formations contain numerous clay layers that provide low strength surfaces on which slip can occur. Landslide movement has occurred on bedding planes with less than 10° of dip when the planes daylighted in road cuts or stream channels.

Over 30 individual landslides or landslide complexes have been mapped along the foothills of Boulder County (Boulder County Planning Commission, 1984). Most of these landslides have occurred on the east slopes of the Dakota hogback and in the cut and natural slopes along the west side of the Lykins Formation strike valley. In the Marshall-Superior area southeast of Boulder, numerous additional shallow landslides have been identified on the slopes blanketed with residual soil and weathered shale of the Pierre and Laramie formations (Figure 11).

Evidence for repeated debris flow activity is present throughout the foothill stream valleys of the Boulder area. Boulders up to 5.8 m (19 ft) in diameter suspended in a poorly sorted matrix of sand and clay have been encountered near the downtown area. The extent of ancient debris flow activity extends as far as 3.2 km (2 mi) east of the foothills, covering a significant portion of the currently urbanized area. No debris flows have been reported since the settlement of Boulder in 1856 (Madole, 1973; Pendleton, 1978), but the possibility of future debris flow activity should not be ignored.

Rockfall is a hazard only in very limited areas. It occurs mainly at high altitudes along valleys with oversteepened sides and in the "narrows" of deep canyons (Madole, 1973). Rockfalls usually occur on spring days that are warm enough to thaw the surfaces of very steep slopes. They also occur during or immediately after intense rains typical of late spring and summer.

Rockfall is mainly a hazard to highway traffic, although some new housing is being built in the vicinity of rockfall susceptible areas, like portions of Boulder Canyon, South St. Vrain Canyon, the Peak-to-Peak Highway and Lee Hill Road where it parallels the Fountain Formation (Madole, 1973). The Penfold subdivision, immediately downslope from the Flagstaff Mountain parklands was threatened by the movement of a 41 metric tonne (45 ton) Fountain Formation sandstone boulder in May of 1972. The boulder had moved approximately 1 meter (3.3 ft) downslope and was precariously lodged against a Ponderosa Pine tree with a 10.2 cm (4 in.) diameter trunk. The City had the boulder broken up by hand at a cost of $6,000. Unfortunately, one 4.1 metric tonne (4.5 ton) fragment of the boulder escaped and damaged the patio and back porch of a home (Pendleton, 1978).

Avalanche hazards in the Boulder area are minimal compared to many other areas of the state. They are mainly confined to the cirques and valleyheads along the Continental Divide (Figure 11). Few well-developed avalanche chutes are present even there. The areas that become dangerous along mountain highways are shot with a cannon to release unstable snow while traffic is restricted.

Mine Subsidence and Mine Fires

Underground mining is the most important cause of subsidence in Boulder County. The magnitude of subsidence has been measured from less than a centimeter to several meters (Amuedo and Ivey, Inc., 1975; Turney and Murray-Williams, 1983). The effects of subsidence include depressions, cracks, and slumping or tilting of the ground surface. Most subsidence has occurred in the sedimentary rocks of the Boulder-Weld Coal Field in southeastern Boulder County (Figures 11 and 14). These reserves are not being developed at present, but may be mined again as future energy needs become more acute.

Many cities in Boulder County can trace their origin to mining. Louisville and Lafayette are two examples of coal mining towns in the Boulder-Weld Coal Field (Figures 1 and 14). The City of Lafayette is underlain by the Simpson Mine, which was first developed in 1888. The site was ideal because it was located only 32 km (20 mi) north of Denver and adjacent to two railroad lines. This mine was capable of an output of approximately 1,220 metric tonnes (1,200 tons) per day. The coal at the Simpson Mine lies in a horizontal plane about 73.2 m (240 ft) from the surface. The coal seam varies from 2.4–4.3 m (8–14 ft) in width, with an average of about 3.7 m (12 ft) of "clean" coal. In April 1906, *Mines and Minerals,* a mining and metallurgical journal published in Scranton, Pennsylvania described this mining operation as follows:

"The system of workings used is that known as the room and pillar method. The roof is rather soft so in driving entries and working rooms only about 9 feet of coal are taken out leaving the remaining 3 feet of coal to support the roof. When the rooms are worked out, the pillars are drawn and this 3 feet of coal is removed with them. With this system of working, little timbering is needed and the cost of production is kept at a minimum. Entries are driven in pairs 10 feet wide, the face entries being 60 feet centers and the butt entries 50 feet. The rooms are 22 feet wide and are worked to a depth of 200 feet. The room necks are 25 feet long. Pillars 18 feet wide are left between rooms and are drawn back after the rooms have been worked to their full length. Very few cross bars are required and in timbering only straight props are used."

This description is representative of the type of mining that occurred in Boulder County during the late 19th and early 20th centuries. When the local cities were founded, little thought was given to the location of structures with respect to the underground workings. Consequently, some buildings, streets and utilities have been damaged due to subsidence over the mines.

Mine fires can be started by natural or human-induced conditions. Once coal is burning in the subsurface it can burn for years or decades. Mine fires have been burning for years less than 4.8 km (3 mi) southeast of Boulder, near the town of Marshall (Figure 1). In that area, collapse of the overlying strata occurs as the fire consumes the coal. This collapse creates cracks and fissures through which oxygen is drawn in to feed the subsurface fire. Smoke and heat can also be released through the subsidence-induced fissures.

The extent, duration, and time of collapse of ground over abandoned underground mines is difficult to predict. Subsidence is generally related to the thickness of the coal removed, mining method used, the structural integrity of overlying rock strata, and the depth of mining. Subsidence has been reported at 41 localities in Boulder County (Boulder County Planning Commission, 1984). An irrigation ditch was affected by subsidence as early as 1941. A 2.4 m (8 ft) deep subsidence depression, measuring approximately 3 m (10 ft) by 6 m (20 ft), appeared in 1964 about 1.6 km (1 mi) west of Louisville (Figure 1). A 4.9 m (16 ft) deep collapse feature, measuring approximately 5.5 m (18 ft) by 7.3 m (24 ft), appeared August 28, 1971, in a mobile home park in Lafayette (Figure 1). In 1974, catastrophic subsidence occurred in Lafayette over subsurface mine workings that had been inactive for more than 50 years. In the Marshall area, where the depth of mining was shallow, collapse has been complete enough to actually discern the pattern of rooms and pillars in the abandoned mine from the surface collapse features.

In 1975, the Colorado Geologic Survey published a map of the subsidence features associated with the Boulder-Weld Coal Field. Using this map and other available mining maps, Boulder County developed a subsidence hazard map for the area. This map has been included in the Boulder County Comprehensive Plan at a scale of 1:158,400 (Boulder County Planning Commission, 1984). The Boulder County Comprehensive Plan and associated comprehensive plans for the mining towns now prohibit new construction in areas designated as having high subsidence potential. Much of the land within the cities of Lafayette and Louisville are zoned as having high subsidence potential. If a structure, for example, is torn down in Lafayette, the county and/or city law requires assurance that no damage due to coal mine related subsidence will affect replacement structures prior to granting a building permit.

An important factor to be aware of in planning any structure above an underground mine is that the surface area affected by subsidence is potentially larger in extent than the area from which the material has been extracted in the subsurface. The determination of the potential for subsidence in areas of previous mining is difficult because the necessary geologic data base is often incomplete and sometimes inaccurate. Mine records of the areas mined, pillars left intact, and air shaft locations were not formalized and, in some cases, have been lost (Ivey, 1978).

Shallow Ground Water

Some areas in Boulder County experience seasonally high ground-water conditions. Where these areas are left undeveloped few problems are encountered; in fact, some areas provide valuable wildlife habitats. When these areas are developed, the most common problem is basement or ground floor flooding. Encountering seasonal water infiltration problems in specific areas around the county encouraged the Building Department to address the problem at the design and permitting stage of development. Regulations now require that the highest ground-water level that might reasonably be expected to occur at the site be shown on the building plans if it was within 3 m (10 ft) of the pre-construction grade. In addition, if this "design ground-water level" was less than 1.1 m (3.5 ft) from the base of a structure, perimeter drains and sump pumps are required to be installed prior to permit approval. The practical result has been the omission of basements in areas of seasonally high ground water in order to keep the base of the structure more than 1.1 m (3.5 ft) from the design water table (Goodell, 1984).

SEISMIC SHAKING

Seismic activity in the Boulder area is considered to be low. According to the Uniform Building Code (1982) all of Colorado is located in Zone 1. This classification implies the following seismic risk: "minor damage; distant earthquakes may cause damage to structures with fundamental periods greater than 1.0 second; corresponding to intensities V and VI on the Modified Mercalli Intensity Scale" (Algermissen, 1969). Major historical events which fall into this category include: Hebgen Lake, Montana (1959); Kosmo, Utah (1934); Helena, Montana (1935); and Elsinore, Utah (1921). Based on the historic record, the potential for a major event (6.5 or greater on the Richter Scale), in the Boulder County area does exist but the recurrence interval ranges from 1,000 to 100,000 years.

Using UBC definitions, the levels of peak horizontal ground acceleration anticipated in the Boulder area should not exceed 0.04 g. This acceleration value represents a 90 percent probability level, indicating there is a 10 percent chance it will be exceeded within any given 50 year period (Algermissen and Perkins, 1976). This is equivalent to a mean return recurrence interval of 475 years or a risk of 0.002 earthquake events per year (Hays, 1980).

Some geologists in Colorado consider the seismic risk classifications based on the historic record of seismicity to be too low. The 110 year seismic history record may be too short to rule out the possibility of a major or moderate earthquake along the Front Range. Other studies suggest that the major faults have had little significant movement since the Laramide orogeny (Jacob and Albertus, 1985). The 1981 report by Kirkham and Rogers on the earthquake potential in Colorado suggests that Colorado should be upraded to Seismic Zone II and that a value of 0.1 g peak ground acceleration is necessary for engineering design purposes. In contrast to Zone I, Zone II classification suggests that moderate damage equivalent to Modified Mercalli Intensity VII is possible for structures with fundamental periods greater than 1.0 second (Uniform Building Code, 1982).

ENVIRONMENTAL CONCERNS

Water Supply

The first water supply for the City of Boulder came directly from Boulder Creek. This creek carried surface runoff water and meltwater from the Arapahoe glacier. A bond issue was authorized in 1874 for the first city water system. Around 1906, the city fathers purchased Silver Lake to get a dependable water supply high enough in the watershed to be relatively pristine. When the city purchased additional watershed land in Roosevelt National Forest in 1929, the purchase included Arapahoe glacier and made Boulder the only city in the U.S. to own a glacier as part of its water supply. Since then, Boulder has acquired the entire watershed, including 11 collector lakes.

Today, Boulder gets its water from three separate sources: the North Boulder Creek watershed; Barker Reservoir, which lies in the Middle Boulder Creek drainage basin; and the Big Thompson diversion complex, which brings water from the western slope of the Rocky Mountains across the Continental Divide (Figure 21; City of Boulder, 1972). The city owns all the land and water rights within the Boulder Creek watershed. This area is closed to the public, so that when consumption demands are high, very pure water can be delivered from Silver Lake to the city with only minimum treatment. A pipeline carries this water down North Boulder Creek to the Betasso Treatment Plant.

Barker Reservoir water is carried by a Public Service Company of Colorado pipeline to Kossler Lake. From Kossler Lake, the water piped across Barker Reservoir is used primarily as a supplemental source during the summer, when demand is high (City of Boulder, 1972; Wheeler, 1984).

The Big Thompson diversion complex was built by the U.S. Bureau of Reclamation in the 1930's. This project transfers water from Grand Lake on the western side of the Continental Divide, through the Alva B. Adams Tunnel, to Lake Estes on the eastern slope. The tunnel is approximately 6.4 km (4 mi) long and about 3.7 m (12 ft) in diameter. Trans-mountain water is strictly controlled and water from the Big Thompson project is managed by the Northern Colorado Water Conservancy District (NCWCD). The district manages 310,000 units per year. A unit yield can vary from a full acre foot to as low as 0.6 of an acre foot, depending on the yield established each spring by the district. Boulder bought water rights or shares of water amounting to about 21,000 units which it stores and treats at Boulder Reservoir.

The city is supported by two water treatment plants, one at Betasso Hill and the other at Boulder Reservoir. After treatment, the purified water is stored in five reservoirs along the foothills above Boulder: Devil's Thumb, Kohler, Chautaugua, Maxwell, and Gunbarrel.

Outside of the city limits and for uses outside of the NCWCD allocations, water supplies most often come from ground-water sources. Unconsolidated aquifers overlie sedimentary rock aquifers in the eastern part of the Boulder area and crystalline rock aquifers in the western part of the area. The Laramie and Fox Hills formations serve as the principal sedimentary rock aquifers in the area.

The unconsolidated aquifers include valley fill, eolian, alluvial, terraced and older alluviums and glacial deposits. They are generally less than 9 m (30 ft) thick but can be as much as 15 m (50 ft) in thickness. Unconfined ground-water conditions predominate in the unconsolidated aquifers and the regional direction of water movement is to the east (Hall et al., 1980). The flood-plain aquifers typically yield supplies of 378.5 l/min (100 gal/min) or more. The glacial and terrace aquifers typically yield supplies of 56.8 l/min (15 gal/min) or more. The valley

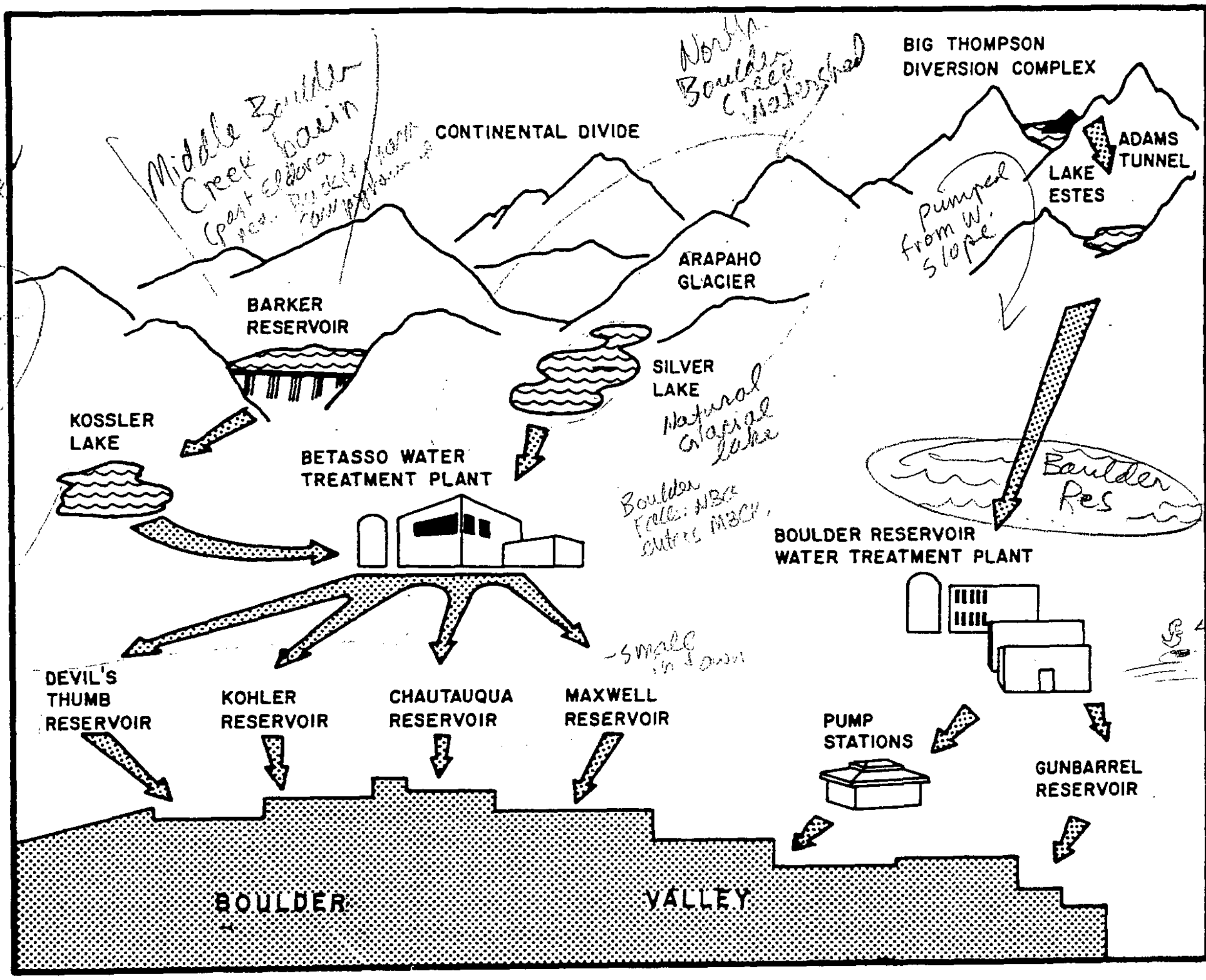

Figure 21. Boulder's water system (from City of Boulder, 1972).

fill and eolian aquifers typically yield supplies of 3.8 l/min (1 gal/min) or more (Hall et al., 1980).

Water in the flood-plain valley fill and glacial aquifers in the mountains is generally suitable for use as a drinking water supply, although bacterial contamination from septic tank leach fields can be a problem. Water in the valley fill, eolian, and terraced or older alluvium aquifers in the plains generally is not suitable for use as drinking water. Excessive concentrations of dissolved solids, sulfate, and hardness are often problems. Locally, excessive concentrations of magnesium, nitrite, nitrate, bacteria, and naturally occurring radiochemicals can be present. Water in the flood-plain aquifer is generally potable in areas just east of the mountain front. Suitability generally decreases eastward (Hall et al., 1980).

The Laramie-Fox Hills aquifer is present only in the southeastern quarter of Boulder County. This artesian (confined pressure) aquifer is about 76 m (250 ft) thick and can yield supplies of 378.5 l/min (100 gal/min) or more. The water from the southwestern portion of the aquifer is generally potable, elsewhere the water is less suitable. Excessive concentrations of dissolved solids and hardness can reduce overall water quality. Excessive concentrations of magnesium, sulfate, trace elements and bacteria are problems locally (Hall et al., 1980).

The crystalline rocks only function as aquifers where they have been fractured to an extent necessary to be permeable. They are present only in the mountains, and well yields vary significantly, depending on location and depth of the well. Water in the crystalline rock aquifers generally is suitable for use as a drinking water supply, though excessive concentrations of dissolved solids, sulfate, hardness, trace elements, bacteria, and naturally occurring radiochemicals can cause problems.

Waste Water Disposal

The City of Boulder has two separate waste water systems. One is for storm water and the other is for sewage, including domestic, commercial and industrial waste water. Storm water is collected and discharged untreated into natural drainages which feed into local streams and rivers. Sewage and industrial waste water within the city limits of Boulder is collected and piped to a waste water treatment plant at 75th and Jay Streets. The plant is capable of treating 59 million l/day (15.6 million gal/day). Hydraulically, the system can handle up to 132.5 million l/day (35 mgd), though this amount of water would not be completely treated if discharged. Normally, 37.9 to 41.6 million l/day (10 to 11 mgd) is treated (Bebler, 1983). The treatment process includes screening, grit removal, clarification, biological treatment, disinfection and, for the sludge, thickening and digestion. Sludge is disposed of through land application.

Solid Waste Disposal

The primary method of disposing of solid waste is by burial in an engineered sanitary landfill. In the Boulder urban area, solid wastes are produced primarily by urban-related activities (as opposed to industrial or agricultural-related activities). Solid waste volumes, therefore, are almost directly related to population numbers. In 1975, people generated approximately 1.9 kg (4.2 lbs) of solid waste per person per day. The estimate for 1985 is 2.3 kg (5 lbs) of solid waste per person per day (Boulder County Planning Commission, 1978). Approximately 355.6 metric tonnes (350 tons) of solid waste per day were generated in 1975. By 1985, due to population increases, it is projected that 635 metric tonnes (625 tons) of solid waste per day will be generated. There are few hazardous waste generators in the county and the volumes of hazardous wastes generated are relatively small.

Boulder County's first solid waste management plan was adopted in September 1971. This plan was developed primarily in response to the urgent need for mountain area waste collection caused by the closure of several open dumps (as opposed to modern, engineered, and permitted sanitary landfills) by the U.S. Forest Service. This plan lead to the elimination of 8 dumps in Boulder County, allowing only 2 to remain open: Marshall landfill and the Golden Rubble Landfill. The other 8 dumps were cleaned up, reclaimed, or simply abandoned. The plan also created the "green box" program, which consisted of the placement of large green dumpsters at centralized locations which served the mountain communities for nearly 10 years. Some of these "green boxes" are still in local use (Boulder County, 1982).

Today there are three certified solid waste disposal facilities that are handling waste from Boulder County. One of these facilities, Marshall Landfill, is located within the county. The other two, Longmont Municipal Landfill and Erie Landfill, are located to the northeast, in nearby Weld County.

The Marshall Landfill is the largest landfill serving Boulder County at the present time (Figure 1). Geology of the site consists of folded and faulted Laramie Formation and Fox Hills Sandstone mantled by 3–6 m (10–20 ft) of Verdos alluvium. The upper Laramie Formation is generally a poor aquifer; in contrast, the lower Laramie-Fox Hills portion of the formation is a moderate to high yield aquifer.

Prior to 1965, the area served as an illegal dump where trash and debris was simply thrown into gullies. From 1965 to 1970, a grinding and composting operation was at the site. Numerous problems resulted from this operation, including a serious problem from windblown debris. South of the original 320 acre landfill, an 80 acre site was developed into a sanitary landfill consisting of compacted soil-covered cells. According to original design plans, surface and subsurface drainage were to be controlled through contour grading and by a system of subsurface interceptor ditches. In addition, clay soil blankets were recommended to seal off all sandstones encountered. A monitoring system and a backup plan were to be provided to control the formation and migration of leachate (Boulder County, 1982). In spite of this design, leachate problems have occurred from this portion as well as older portions of the landfill (Noack, 1984). Leachates have drained into Community Ditch. This ditch occasionally adds water to the Louisville municipal water supply. The U.S. Environmental Protection Agency (EPA) has included Marshall Landfill on the National Priority List of Superfund sites. In addition to surface water contamination, ground water contamination is also suspected.

At the present time, the EPA, State Health Department, and Boulder County Health Department are attempting to determine the precise extent and specific sources of water pollution. In July of 1981, the Public Works Department developed surface drainage improvements designed to prevent direct flow of leachate into Community Ditch. As a result of these improvements, the City of Louisville was allowed to continue using the water from Community Ditch (Boulder County, 1982). A pipeline was built in the fall of 1984 to safeguard Louisville's water supply by isolating it from the leachate. Boulder County, the City of Louisville, and the landfill operator, Browning Ferris Industries, shared the cost of pipeline construction. EPA Superfund money is also available for site remediation. In the meantime, the landfill will continue to be used. It is presently estimated that the landfill has the capacity to remain open and operating until 1989.

The Golden Rubble Landfill covers approximately 16.2 ha (40 acres) within the City of Longmont. This site was used as a rubble dump prior to designation as a sanitary landfill in November 1969. The site remained active until April 1976. Approximately 95 percent of the fill material is rubble consisting of concrete, wood, and construction and demolition debris. The remaining 5 percent of the fill material consists of office wastes and household items which are non-putrescible. This landfill is not currently in use (Boulder County, 1982).

The Boulder County "green box" program was developed in 1972 to serve tourists and residents in the mountain area from Nederland to Allenspark. The original phase of the program consisted of providing 30 trash containers, each with a capacity of 4.6 m^3 (6 yds^3) at 18 selected sites along state highways and county roads for pickup by a private hauler. 44,468 m^3 (34,000 yds^3) of trash were hauled in the first 12 months of operation with noticeable reduction of roadside litter. The program received the National Association of Counties Achievement Award in 1973. In the latter part of 1980, the Board of County Commissioners (BCC) initiated the gradual phaseout of the green box program because of program costs and declining effectiveness. Some green box sites remain and the BCC has instituted user fees to cover hauling costs (Boulder County, 1982).

Collection and transportation of solid waste in the Boulder area is accomplished primarily by private contract haulers. The city of Longmont provides a municipal collection service for residential solid waste and the City of Boulder provides hauling of spring cleaning debris each year for city residents (Boulder County, 1982).

Beginning in 1983, Boulder County began conducting a county wide search for additional landfill sites. Geologic and hydrologic compatibility are high priority issues that the county is considering through the selection process. At this time, final site selection has not been made.

Wetlands Factors

Wetlands are defined as land where an excess of water is the dominant factor determining the nature of soil development and the types of plant and animal communities living at the soil surface. Thus wetlands in Boulder County include marshes, swamps, bogs, wet meadows, pot holes, sloughs, river-overflow lands, reservoirs, lakes, and streams. Wetlands are valuable to waterfowl breeding, wintering and migration habits. They can also store ground water, stabilize runoff, retain surface water, and reduce erosion. Wetlands were inventoried for Boulder County in 1977 prior to the development of the County's Master Plan. Protection of these wetlands is not guaranteed through the Master Plan, although it is generally the policy of the county to preserve these areas whenever possible (Boulder County Planning Commission, 1978).

MAJOR ENGINEERING STRUCTURES

Due to the height limitation of buildings in the City of Boulder, there are few structures which are more than 7 stories high. A notable exception to the height ordinance are the dormitories associated with the University of Colorado, Williams Village complex (Figure 22). These four dormitories range in height from 11 to 15 stories. The complex was exempt from the city and county height restriction because it was constructed on state land. Each dormitory has a basement and is founded on drilled piers approximately 1.2 m (4 ft) in diameter and approximately 15.5 m (50 ft) long.

USE OF UNDERGROUND SPACE

The use of underground space in Boulder has been primarily limited to basements and below grade parking. No other plans for the use of underground space are currently under consideration by city or county planners.

ENGINEERING GEOLOGIC PRACTICE IN BOULDER

Legislation

In 1972 the Colorado General Assembly enacted Senate Bill 35, which requires an investigation of the geologic factors that would impact any proposed

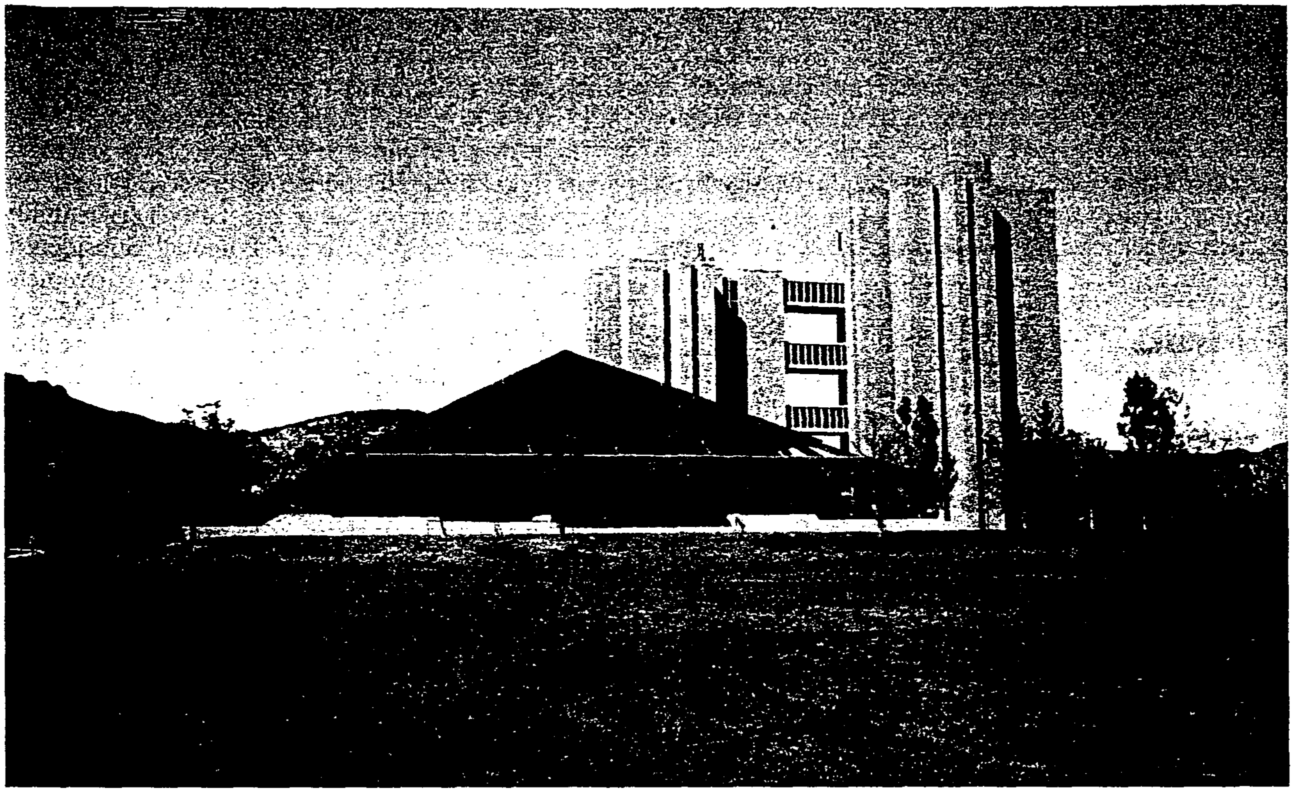

Figure 22. Williams Village dormitory towers, University of Colorado.

new subdivisions in unincorporated areas of the state. Since that time, most geologic reports have been prepared by geotechnical consultants for subdivisions and/or land developers. These reports are submitted to county planning departments, which usually submit them to the Colorado Geological Survey (CGS) for review and comment. In July 1983, the CGS began to charge $160 to $275 for this service. Approximately four CGS geologists spend a major part of their time conducting these reviews and are recognized as specialists in the areas of the state that they evaluate (Rogers, 1984). Approval or disapproval of a subdivision rests solely with the county, however, and the Colorado Geological Survey has no regulatory authority over their decision.

In 1973, House Bills 1529 and 1065 were enacted. House Bill 1529 precluded any governmental agency from zoning for exclusive use any area of mineral deposits, including sand and gravel deposits, deemed to be of economic or strategic importance. The bill also required the local government to develop a master plan for extraction of the deposits. The thrust of this bill was directed toward extraction of aggregate resources in the urbanizing areas of the state prior to development. House Bill 1065 established the Colorado Mined Land Reclamation Board to ensure proper reclamation of mined-out areas in the state.

In 1974, House Bill 1574 was passed, requiring that all geologic reports prepared for government review be done by a "professional geologist." A "professional geologist" was statutorily defined as an individual with at least 30 semester hours of undergraduate geological education and five additional years of experience which could include no more than two years of graduate work. In 1973 and again in 1976 attempts were made to enact a geologist-registration law in Colorado, but both failed.

House Bill 1041, requiring the Colorado Geologic Survey to assist local governments in identifying and designating geologically hazardous areas, also passed in 1974. Areas subject to avalanches, landslides, rockfalls, mud and debris flows, unstable slopes, seismicity, radioactivity, subsidence, expansive rock and soil, and mineral resource areas were included under the law. The law legally defined geologic hazards and authorized cities and counties to manage activities in geologic-hazard and mineral resource areas. A related bill, HB 1034, which also passed in 1974, empowered cities and counties to consider geologic hazards when regulating development and other activities in their jurisdiction (Rold, 1984).

In 1976, the City of Boulder made history by adopting a policy to limit growth of the population to 2 percent per year. This policy was enacted through a limitation on the allocation of building permits. From 1976 to 1981, the "Danish Plan" was used, whereby the builders in the area had to compete for a limited number of building permits. The projects to receive building permits were chosen on the basis of merit and location; that is, were they designed according to the best interests of the city and whether they were close to existing city services. From 1981 to 1984, the "Residential Growth Management System" was used. With this system the builders got preferential consideration if they designed moderate income housing or energy efficient housing. Phasing, or how close the project was to completion, was also a criterion in selection. Presently, the city is revising the Residential Growth Management System, although it is not expected to change substantially (Pollock, 1984). There have been numerous legal and moral challenges to the growth limitation policy, but so far the city is steadfast in using building permit allocation to follow the electorate's wishes to limit growth to 2 percent per year.

City Geologist

In 1967, the City of Boulder requested assistance from the U.S. Geological Survey (USGS) to evaluate a foothills subdivision proposal. The USGS persuaded the city to hire a geology graduate student at the Colorado School of Mines, on a part-time basis, to map open utility trenches and to compile a geotechnical map of the city. The Utility Department was especially receptive to any geotechnical input that would reduce their capital losses resulting from landslides, swelling soils, or ground subsidence. From 1969 to 1971, this staff geologist position was funded from the Utility Department's general overhead expenses. From 1971 on, the position was funded partially by direct charges to projects for geotechnical design services. In 1974, the city funded an "Urban Geology" program to analyze all geotechnically related engineering failures, to analyze and inventory all geologic hazards, to address resource conservation, and to compile single purpose derivative geotechnical maps of the urban area, among other things. By 1975, the job title "Geologist" was officially created and the job was indicated as a full-time, permanent position on the staff of the Engineering Division (Pendleton, 1978).

Eight single purpose derivative geotechnical maps were developed: Simplified Bedrock Geology, Potentially Extractable Sand and Gravel, Potentially Extractable Coal, Areas of Potential Subsidence, Consolidation/Swell Potential, Mass Movement Hazards, Geology of the Boulder Area, and a Master Plan for Mineral Extraction. These maps were produced at a 1:12,000 scale for the 312 km^2 (120 mi^2) urban area (Pendleton, 1978). These maps were used extensively when the comprehensive plan for the city was developed. An effort was made to place geologically hazardous areas in open space or to restrict them to other nonurban uses. Critical mineral resources were similarly protected (Rose, 1984).

In December 1979, the City Geologist resigned and he has not been replaced. The position was eliminated in a budgetary cut. Presently, the maps developed by the City Geologist are available only for reference and are not used in a formalized manner.

County Geologist

When the Colorado Legislature approved House Bill 1041, the General Assembly also appropriated funds to subsidize counties in application of the law (Pendleton, 1978). Boulder County used these funds (approximately $25,000) to hire a staff geologist in November 1975. He developed two maps: the Mineral Resource Areas map and the Geologic Hazard and Constraint Areas map for inclusion in the 1978 Comprehensive Plan. These maps were not traditional geologic maps but, rather, maps designed for use in long range planning by people not necessarily familiar with geology. The Mineral Resource Area map consists of general divisions which include coal resource areas, aggregate resource areas, and lode mineral areas (Figure 14). The Geologic Hazard and Constraint Area map consists of four relative geotechnical ratings of the entire county, ranging from major-extensive problems and high risk to minor-few problems and nominal risk (Figure 23). In addition to the four rankings, the map contains symbols which indicate the specific geologic hazard or constraint present, such as "l" for landslide or "x" for expansive soil. These maps are available through the county.

In conjunction with the Building Department, the