# ENGINEERING GEOLOGY OF THE SALT LAKE CITY METROPOLITAN AREA, UTAH

WILLIAM R. LUND
Editor

BULLETIN 126 1990
UTAH GEOLOGICAL AND MINERAL SURVEY
*a division of*
UTAH DEPARTMENT OF NATURAL RESOURCES
***in conjunction with***
THE ASSOCIATION OF ENGINEERING GEOLOGISTS

***COVER PHOTO:*** *Aerial view of the Salt Lake City metropolitan area looking southeast along the front of the Wasatch Range and the Wasatch fault zone. The mountain front marks the boundary between the Basin and Range (right) and Middle Rocky Mountains (left) physiographic provinces. Valley area is the former bed of Pleistocene Lake Bonneville (photograph credit, Great Mountain West Supply).*

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# ENGINEERING GEOLOGY OF THE SALT LAKE CITY METROPOLITAN AREA, UTAH


**WILLIAM R. LUND**
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WILLIAM R. LUND

## PREFACE

The Utah Geological and Mineral Survey (UGMS) is pleased to publish Bulletin 126 "Engineering Geology of the Salt Lake City Metropolitan Area" in conjunction with the Association of Engineering geologists (AEG). This manuscript was originally prepared for the AEG "Cities of the World" engineering-geologic series and was published in the *Bulletin of the Association of Engineering Geologists* (Volume XXVII, Number 4, November, 1990) as "Geology of Salt Lake City, Utah." Recognizing that a publication of this nature would be of interest to a broad audience, the UGMS and the AEG agreed that the UGMS should also publish the paper to make it readily available to the general public.

Only a few changes have been made in the original AEG paper for its publication by the UGMS. Because the paper is chiefly concerned with the engineering geology of the entire Salt Lake City metropolitan area (the Salt Lake Valley and adjacent mountain canyons), and is not a comprehensive treatment of all aspects of the area's geology, the title has been changed for the UGMS Bulletin to more accurately reflect the content of the publication and its geographic coverage. Those readers with a particular geologic interest are referred to the extensive reference list at the end of this publication. Two references in particular, UGMS Bulletin 69 "Geology of Salt Lake County" edited by A.L. Crawford (1964) and Utah Department of Natural Resources Technical Publication 31 "Water Resources of Salt Lake County" by Hely and others (1971), provide much additional information on the geology and hydrology of the study area.

Unlike the original AEG paper, the author(s) of each section of this bulletin have been acknowledged to provide proper credit for the many hours of hard work they contributed, often in addition to their regular duties, to the successful completion of this publication. As Editor, I thank each of them for their unstinted efforts and enduring patience.

William R. Lund
Utah Geological and Mineral Survey

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## FOREWORD

Salt Lake City has the unique geologic setting of being sandwiched into a 9-mile (15-km) wide corridor between the greatest inland sea of the western hemisphere and the crest of a still-rising mountain range. Growth of the city is constrained geographically by the Great Salt Lake, which fluctuates dynamically in its area of coverage, and 7100 feet (2175 m) of rugged mountains, the twain of which are bounded by an enigmatically active, intraplate fault zone.

Mormon religious pioneers founded Salt Lake City less than 150 years ago (1847) as a planned community based on favorable exploration reports of U.S. Army Captain John C. Fremont, whose scientific expeditions reached the area in 1843 and again in 1845. All the ingredients of livelihood were available, abundant surface water, arable soil, timber, water power, and dimension stone. Earth materials are here represented by a full range of sedimentary, igneous, metamorphic, and volcanic rocks (Precambrian through Tertiary), and a variety of cohesionless and cohesive soils. Rocks were "piled up" in the area by regional compression and thrust faulting up to mid-Eocene time, followed by formation of the Salt Lake basin by normal faulting beginning in Pliocene time. This faulting was of sufficient magnitude to override the presence of the east-west-trending Uinta arch, a major North American tectonic feature dating from post-Late Precambrian time. Of historical geologic processes, we can certainly say that the Salt Lake Valley has seen competition from strong opposing forces, most of which have been driven by crustal events covering millions of square miles.

Perhaps the least understood, although long recognized, geologic factor of the Salt Lake Valley is its position at the eastern border of the Basin and Range physiographic province. Any geologist, on first or second reflection, will proclaim that physiographic boundaries are places at which geologic processes are most likely to be dynamically active, and so is the case of the Salt Lake Valley. Geologists and seismologists have not yet completely worked out

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the riddle of the valley's pulse, but regional tectonic stresses are forcing the Wasatch Range upward, and the Salt Lake basin may be an actively subsiding graben. Thus, while the mountain range rises, earthquakes of significance can be expected; while the basin subsides, the Great Salt Lake has the potential to expand and flood the City's lakeshore. Upward tectonism of the mountains gives them a renewed topography, the ruggedness of which keeps active a host of geologic constraints which produce flooding, rockslides, debris flows, and slope instability.

Situated between the lakeside and the mountain crest, many of Salt Lake City's citizens view the mountainsides as an inviting domicile. Lessons learned in the soft-rock hillsides of Los Angeles in the early 1950s are being re-learned here as city and county officials and the geological and geotechnical community strive to lead the way to responsible utilization of the remaining land, most of which is made marginally suitable by geologic constraints.

The most preeminent of Salt Lake City's geologic features is the Wasatch fault zone (WFZ), centerpiece of the Intermountain seismic belt (ISB). The WFZ appears to be the key (first-order) force driving the behavior of the Wasatch Range and to some extent the Great Salt Lake. The mountain range and lake, as second-order forces, drive a litany of third-order geologic influences: collapse-prone soils, compressible soils, low-strength soils, liquefiable soils, and lake flooding.

Earthquake risk is well recognized by the scientific and engineering community and by many public officials, if not by the general public. Most experts proclaim that a maximum credible earthquake (MCE) has not occurred in historical time; the question of where and when the MCE will occur is the subject of much study and concern. The WFZ gives abundant evidence that it behaves independently, in terms of strain release, along a number of rather short segments 15 to 40 miles long (20-70 km). The surface of active faults may be seen and inspected in valley-bounding highway cuts, gravel pits, and quarries. This prominence should well keep the public interested in preparation for future damaging earthquakes, for the Wasatch Range has been faulted upward for an estimated 36,000 feet (11,000 m) since post-Oligocene time. Exploratory trenching and geomorphic studies have shown that numerous large (M = 7.0-7.5) earthquakes have caused this uplift. Considering this capability, coupled with the fact that ISB earthquakes typically occur as shallow (less than 10 miles or 16 km) events, the spectrum for high levels of damage through ground rupture and ground shaking (to 0.35 g on soft ground) is large. Five billion dollars of damage have been predicted as the basis for earthquake risk planning. No wonder the famous 19th century U.S. Geological Survey geologist Grove Karl Gilbert proclaimed, in 1883, that the city would be destroyed before its citizens would learn to design in mitigation.

Local geologists and engineers have striven to emplace appropriate seismic-withstand design requirements. Progress is being made but, as of yet, only the Uniform Building Code requirements for seismic zone 3 have been adopted by elected officials.

Salt Lake City's geologic and engineering community has carried the need for scientific regulation of urban expansion forward through a number of workable measures. Salt Lake City actually has one of the greatest needs for geologic regulation of any American city. For mitigation of geologic hazards, forthcoming regulations will need to continue to recognize the geotechnical complexity of foundation engineering units. Colluvial and alluvial units are typically lensed, and they have been extensively channelled and filled, as well as left isolated at higher elevations under terraced geomorphic surfaces. Geotechnical engineering is therefore based on the need for careful examination of every building site and the representative exploration of all portions of each site. A broad variety of foundation designs are employed to counter the unusual variations in soil stratigraphy and the lateral extent of foundation units.

A patchwork of mitigation measures have been initiated at the city and county levels; recognition of faults (all of which are initially presumed to be active), unstable slopes (mainly in Mesozoic sedimentary rocks and lacustrine sediments), localized floods and debris flows in canyons, avoidance of Federal Emergency Management Agency 100-year flood inundation boundaries, and setbacks from the lake shore.

The complexities of foundation soil units are also typical concerns for ground-water supply and for design and remediation of waste-management facilities. Valley ground-water supplies have not yet been fully characterized nor subjected to serious withdrawal. The semi-arid climate is favorable to maintenance of low-leachate-generation conditions, and clay-rich soils are advantageous for landfill siting, yet site complexities must be respected by careful site characterization. Most hazardous-waste remediation is underway at existing or former plant sites, rather than at waste disposal facilities. Considerable effort is being spent in planning and remediation of special waste sites represented by the mineral industries. Mining activities have been dominated by the world-class, open-pit, Bingham copper mine, from which almost 0.7 mile$^3$ (3 km$^3$) of rock and soil have been removed and processed to metals and tailings since 1906.

Citizens of Salt Lake City can take pride in bringing their pioneer model to the status of a major city; however, continued growth and the ticking clock of crustal stress accumulation along the WFZ indicate that "interesting times" indeed are in store for the residents of the Salt Lake Valley. Geologists and geotechnical engineers of the city are aware of the needs and measures which will be required to protect the citizenry. May the people of Utah and their elected officials heed their messages.

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# ABSTRACT

Salt Lake City is the capital of Utah and a major financial, trade, and transportation center for the western United States. Founded in 1847, Salt Lake City presently (1990) has a population of about 158,000. However, the metropolitan area of the city, which includes most of the Salt Lake Valley, contains both incorporated and unincorporated suburbs that increase the population to nearly 705,000.

Geologic exposures in the Salt Lake City region record a long history of sedimentation and tectonic activity extending back to the Precambrian Era. Today, the city lies above a deep, sediment-filled basin flanked by two uplifted range blocks, the Wasatch Range and the Oquirrh Mountains. The Wasatch Range is the easternmost expression of major Basin and Range extension in north-central Utah and is bounded on the west by the Wasatch fault zone (WFZ), a major zone of active normal faulting. During the late Pleistocene Epoch, the Salt Lake City region was dominated by a succession of inter-basin lakes. Lake Bonneville was the last and probably the largest of these lakes. By 11,000 yr BP, Lake Bonneville had receded to approximately the size of the present Great Salt Lake. Lake Bonneville sediments bury most older deposits in the valley below an elevation of about 5200 feet (1585 m). Lake sediments include near-shore beach, delta, spit, and bar deposits and silt and clay deposited in deeper water. Post-Bonneville deposits include Holocene alluvium along the Jordan River and its tributaries and alluvial fans along mountain fronts.

Repeated normal-slip faulting has occurred at the ground surface in Utah during late Pleistocene and Holocene time. Most of this activity has been on the WFZ which traverses the Salt Lake City metropolitan area. West-facing scarps of a few to tens of feet high are common, as are graben, horsts, and other fault-related features. Paleoseismic data show that the average recurrence interval for surface-fault displacement on the Salt Lake City segment of the WFZ is 4000 ± 1000 yr. However, the City can expect to experience strong ground shaking associated with a large earthquake somewhere on the WFZ every 340 to 415 years. The West Valley fault zone (WVFZ) is an east-dipping, normal fault that trends to the north-northwest through the central part of the Salt Lake Valley. The WVFZ has had at least six surface-faulting events in the past 13,000 years. Despite the close proximity to active faults, Salt Lake City has not yet been subjected to a large, destructive earthquake. Felt events have occurred, but only a few have caused appreciable damage.

Geologic units in the Salt Lake City metropolitan area generally provide adequate foundation conditions. The principal foundation problems are compressible, low-bearing-strength soils; collapse-prone soils; and liquefaction. Some shale units and the soils derived from them may be expansive. Use of underground space is restricted to the nearby Wasatch Range and Oquirrh Mountains and includes storage of documents and valuables, water storage, and mining-related uses.

Numerous geologic hazards exist in the Salt Lake City metropolitan area. Movement on faults may cause ground rupture, ground shaking, tectonic displacement, ground failure including liquefaction, and seiches on the Great Salt Lake. Steep slopes create the potential for landslides, rock falls, debris flows, and snow avalanches. Streams and the Great Salt Lake experience flooding, and high ground-water conditions are common.

Water for the Salt Lake City metropolitan area comes principally from streams in the Jordan and Colorado River drainages. Ground water from wells and springs is also used. Major surface storage reservoirs are considered inadequate and additional storage is being constructed. Basin-fill aquifers provide the largest existing source of stored water.

Most of the Salt Lake City metropolitan area is served by public sewers. Wastewater is treated at municipal treatment plants and solid waste is placed in county and municipal sanitary landfills. Hazardous waste sites include disposal sites for cement kiln dust; mine, smelter, and oil refinery wastes; and various chemical wastes. Three hazardous waste disposal sites are on the Environmental Protection Agency's Superfund National Priority List.

Mineral resources have played an important role in the development of Salt Lake City. A variety of salines and metals are recovered from Great Salt Lake brines. The Bingham mining district in the Oquirrh Mountains is one of the world's largest copper producers. The Big and Little Cottonwood mining districts and the Hot Springs mining district, all in the Wasatch Range, are no longer active, but have produced a variety of precious and base metals. Industrial rocks and minerals include cement, construction aggregate, crushed stone, industrial sand, and clay. The oil and gas potential of the Salt Lake Valley has not been thoroughly explored but probably is low. Geothermal water is used to heat greenhouses and part of the Utah State Prison.

The Great Salt Lake presents Salt Lake City with unique geologic hazards and engineering-geology problems. Fluctuations in lake level occur daily, seasonally, and on a long-term basis. The rise of the lake during the period 1983-1985, due to above-normal precipitation, caused over $240 million damage and initiated construction of the West Desert Pumping Project. In addition to flooding, development near the lake must also consider the effects of earthquakes on the lake and sensitive lake-bottom sediments, low-bearing-strength soils, and rafting-ice impact on lake structures within the lake.

# INTRODUCTION

*William F. Case*

## SETTING

Salt Lake City, the capital of Utah, is a major financial, trade, and transportation center for the western United States. Located in northern Utah at latitude 40°45′N., longitude 111°52′ W., the incorporated area of Salt Lake City encompases 109 miles$^2$ (282 km$^2$) at the north end of the Salt Lake Valley (figure 1). The population of Salt Lake City is about 158,000 (Hanson, 1989). However, metropolitan Salt Lake City includes most of the Salt Lake Valley (764 miles$^2$; 1979 km$^2$), and contains numerous incorporated and unincorporated suburbs that bring the population of the metropolitan area to nearly 705,000 (Hanson, 1989). Metropolitan Salt Lake City is the subject of this report.

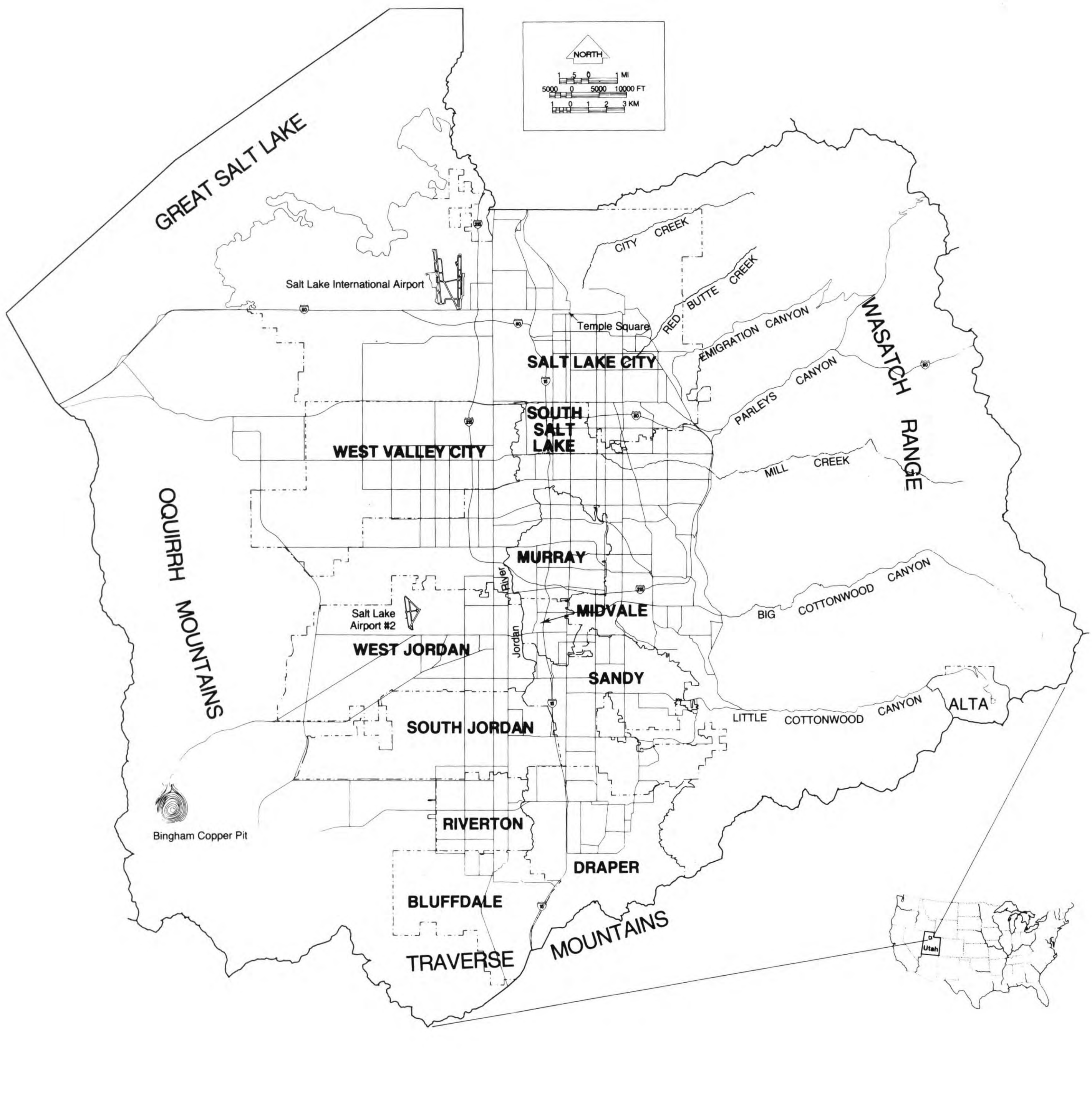



*Figure 1.* Index and location maps of the Salt Lake City metropolitan area (Salt Lake Valley).

The Salt Lake Valley is about 25 miles (40 km) long and 16 miles (26 km) wide (figure 1). The borders of the valley are defined by mountain divides on the east, west, and south, and by the Great Salt Lake on the north. The eastern edge of the valley is delimited by the precipitous Wasatch Range that marks the boundary between the Middle Rocky Mountains and the Basin and Range physiographic provinces (Stokes, 1977). Maximum relief in the valley is 7134 feet (2175 m) from the historic low of the Great Salt Lake at 4191 feet (1277 m) to the highest point in the adjacent Wasatch Range at 11,325 feet (3452 m). The Oquirrh Mountains form the western side of the Salt Lake Valley. At approximately 20 miles (32 km) in length, these peaks reach elevations up to 9360 feet (2853 m). The southern border of the Salt Lake Valley is marked by the Traverse Mountains (figure 1), which are 10 miles (16 km) long and reach an elevation of 6829 feet (2082 m).

Most of the surface water entering the Salt Lake Valley comes from high drainage basins to the east in the Wasatch Range. Price and Jensen (1982) identify seven perennial Wasatch Range streams (Little Cottonwood Creek, Big Cottonwood Creek, Mill Creek, Parleys Creek, Emigration Creek, Red Butte Creek, and City Creek; figure 1) that enter the Salt Lake Valley with peak flows that exceed 50 feet$^3$/sec (1.4 m$^3$/sec). Oquirrh Mountain streams are ephemeral and contribute little to the surface-water resources of the valley. All surface drainage flows to the Jordan River and then to the Great Salt Lake. The Jordan River originates at Utah Lake and enters the Salt Lake Valley from the south (figure 1). The maximum discharge of the Jordan River into the Salt Lake Valley is 1410 feet$^3$/sec (40 m$^3$/sec) (Price and Jensen, 1982). The Great Salt Lake occupies the lowest point of a closed basin and, in addition to the Jordan River, receives inflow from the Weber and Bear Rivers which drain parts of western Wyoming, southeastern Idaho, and northeastern Utah.

Natural vegetation in the Salt Lake Valley includes oak, maple, juniper, sagebrush, bunch grass, and shadscale on the valley floor and in the mountain foothills. Spruce, fir, and aspen are found at higher elevations in the Wasatch Range (Foster, 1968).

Salt Lake City was a planned community from the beginning, much like many American cities of the same era (Alexander and Allen, 1984). The streets follow a grid pattern parallel to the cardinal directions with 20 acre (8 ha) city blocks. Street names are reported as the number of blocks and direction from Temple Square in the center of the downtown area. The central business district was originally the hub of administrative and business activity with the remainder of the valley devoted to agriculture. Residential and business growth has gradually replaced most agriculture land use in the valley. In recent years, many facilities, particularly large department stores and professional offices, have moved to outlying parts of the metropolitan area. However, a number of new high-rise buildings with professional offices, penthouse condominiums, and ground-floor shopping have been built in downtown Salt Lake City, indicating a resurgence of urban living. Residential growth now favors higher elevations along topographic benches to the north, east, and southeast of the downtown area, and toward the south and southwest portions of the Salt Lake Valley. Many suburban communities in the Salt Lake Valley originally located along transportation routes leading to Salt Lake City have now grown together but remain administratively separate from Salt Lake City.

The 1980 population of metropolitan Salt Lake City was 615,586, representing 42 percent of the population of Utah (Gurgel, 1981). Wahlquist (1981) reports the 1980 population density of the Salt Lake City metropolitan area as approximately 788 persons/mile$^2$ (304 persons/km$^2$) compared to an average Utah population density of about 17 persons/mile$^2$ (7 persons/km$^2$). Table 1 is a list of present-day incorporated communities in the Salt Lake City metropolitan area with their founding date and 1986 population (Hanson, 1989); most are now suburbs of Salt Lake City (figure 1). Many other developed areas within the Salt Lake Valley form an integral part of the Salt Lake City metropolitan area but remain as unincorporated areas of the county.

Salt Lake City boasts a Federal Reserve branch bank; customs port and foreign trade zone; international airport; stock exchange; state institutions of higher education including the University of Utah, Salt Lake Community College, and nine private colleges or branches of other universities. Transportation lines include north-south Interstate Highway I-15, east-west Interstate Highway I-80, and Union Pacific and Denver and Rio Grande Western rail lines. The city also supports the Utah and Salt Lake Symphonies; professional basketball, hockey, and baseball teams; and several classical dance companies, including the world renowned Ballet West.

**Table 1.**

Year of founding or incorporation and 1986 estimated population and rank in Utah of metropolitan Salt Lake City communities (Kirkham and Lundstrom, 1947; Ellsworth, 1985; Hanson, 1989).

| Community | Year Founded | 1986 Population | 1986 Population Utah Rank |
|---|---|---|---|
| Salt Lake City | 1847 | 158,440 | 1 |
| West Jordan | 1848 | 44,440 | 7 |
| Draper | 1849 | 6040 | 39 |
| Midvale | 1851 | 11,390 | 24 |
| Bluffdale | 1865 | 2060 | 92 |
| Alta | 1867 | 460 | 162 |
| Sandy | 1871 | 67,430 | 5 |
| Riverton | 1879 | 9470 | 32 |
| Murray | 1902 | 23,730 | 11 |
| South Jordan | 1935 | 11,030 | 29 |
| South Salt Lake | 1938 | 12,340 | 22 |
| West Valley City | 1980 | 90,770 | 2 |

*Note: Communities of population rank 3 and 4 are Ogden and Provo, respectively.*

## CLIMATE

The climate of Salt Lake City is a function of latitude, elevation, topography, and distance from moisture sources. According to the modified Koeppen Climate Classification (Critchfield, 1974), Salt Lake City is on the border between a semi-arid, mid-latitude steppe climate that occurs along the perimeter of the Great Basin Desert and a humid, continental climate found at slightly higher elevations in the Rocky Mountain foothills. Weather records for Salt Lake City reflect the characteristics of a western continental interior climate near the 40th parallel (four seasons, low annual precipitation, convective and frontal storms, dry summers, low humidity, and large annual and diurnal temperature extremes). Annual sunshine averages 70 percent of possible. Precipitation is directly related to elevation, with the 30-year normal (1951-1980) annual precipitation at the Salt Lake City International Airport (4222 feet; 1287 m) at 15.3 inches (38.9 cm) (National Climatic Data Center, 1986). Average annual precipitation immediately adjacent to the city in the Wasatch Range is 40 inches (101.6 cm) (Glines, 1970). Not all precipitation falls as rain; the airport averages 58.9 inches (149.6 cm) of snow annually. The maximum snowfall recorded to date occurred during the 1983-84 season when 835.4 inches (2121.9 cm) of snow fell at the town of Alta (figure 1) in the Wasatch Range (Eubank, 1986).

## HISTORY OF FOUNDING

On July 24, 1847, with the words "This is the right place. Drive on," (Ellsworth, 1985) Brigham Young, leader of the Church of Jesus Christ of Latter-day Saints (LDS), instructed the Pioneer Company to descend Emigration Canyon (figure 1) and enter the Salt Lake Valley to establish a permanent settlement and refuge for the followers of the LDS (Mormon) faith.

The Mormons were not the first to occupy the Salt Lake Valley. Indian tribes descriptively named Desert Gatherers or "diggers" subsisted on small animals, insects, seeds, and roots as they roamed northern and western Utah as early as 9000 BC (Ellsworth, 1985). The Fremont Indians lived in central and northern Utah between the years AD 500 and approximately AD 1300. The Fremont were Desert Gatherers who borrowed advanced techniques such as domestication of plants and construction of granaries and dwellings from the Anasazi Indians of the Colorado Plateau. After AD 1300, the Fremont and Anasazi cultures disappeared, but the simpler Desert Gatherer culture remained. In historical time, the Salt Lake Valley was a neutral ground between the Goshute Indians, who lived in northern and western Utah, and the more aggressive Timpanogos Utes from Utah Valley, located just south of the Salt Lake Valley. The Utes roamed as far east as the Great Plains on horses descended from those left by Spanish explorers. The names of the Oquirrh Mountains and Wasatch Range reflect Utah's Indian heritage; Oquirrh is a Goshute word meaning "wooded mountain," and Wasatch is a Ute word meaning "low pass over a high mountain" (Ellsworth, 1985).

By the time the Mormons arrived in the Salt Lake Valley, the region, which would not formally become a part of the United States until the next year, had been explored by parties from Mexico, the United States, and Canada. The 1776-77 Dominguez-Escalante expedition explored southern and central Utah in search of a supply route from Santa Fe, New Mexico to the Spanish missions in California (figure 2). Although they did not travel north of Utah Valley, Don Bernardo Miera y Pacheco, the expedition mapmaker and astronomer, used Indian accounts to portray a large lake to the north connected by a river (Jordan River; figures 1 and 2) to the lake (Utah Lake) in Utah Valley. On his map, Miera labelled the northern lake Timpanogos and included a mythical river which drained the lake to the west. Lake Timpanogos and the western drainage persisted on published maps until exploration by fur trappers from the United States in the 1820s proved that the Great Salt Lake had no outlet. In addition to American fur trappers, parties from Hudson Bay Company outposts in the Columbia River drainage travelled and trapped extensively in the Salt Lake City region. John C. Fremont, the first scientific explorer of the area, examined the Great Salt Lake in 1843 and camped on the future site of Salt Lake City in October, 1845 (Ellsworth, 1985). Fremont's descriptions of the region were widely read in the United States and contributed to the initial interest of the Mormons in the area.

Prior to 1846, most overland travelers to California followed the Oregon Trail into southern Idaho and then turned southwest toward California (figure 2). In 1846, Lansford W. Hastings promoted a route taken by Fremont around the south end of the Great Salt Lake (Hastings Cutoff; figure 2). The first wagons to use the ill-advised Hastings Cutoff crossed the Wasatch Range through narrow Weber Canyon before proceeding south through the Salt Lake Valley and west past the Great Salt Lake to California (figure 2). The Donner-Reed Party, attempting to use the Hastings Cutoff, spent valuable days in August, 1846, cutting a road from the Weber River to Big Mountain and over Donner Hill at the mouth of Emigration Canyon. As a result, the ill-fated emigrants were trapped by early snow storms in the Sierra Nevada Range of California, where most perished. Eleven months later, after following portions of the Oregon and California Trails (figure 2), the Mormons improved the Donner-Reed Road and used it to enter the Salt Lake Valley. Later, many California-bound travelers elected to follow this route to Salt Lake City and then turn north to rejoin the California Trail north of the Great Salt Lake.

By the time Brigham Young reached the Salt Lake Valley, the vanguard of the Pioneer Company, which arrived three days earlier, had plowed fields, planted seeds, constructed an irrigation dam on City Creek, and established a camp between two forks of City Creek near the present site of Temple Square (figure 1). After a few days spent reconnoitering the valley, the pioneers elected to establish Great Lake City of the Great Basin, North America at their original camp near the mouth of City Creek Canyon. By 1868, the name had been changed by the Utah Territorial Legislature to Salt Lake City.

During the first winter, most cabins were constructed within a stockade named the Old Fort, and the city had a population of nearly 1700 (Ellsworth, 1985). By the summer of 1848, a number of other settlements had been established in the Salt Lake Valley (table 1) and the population of Salt Lake City was approaching 3200. Topography encouraged commerce when immigrant trails passing through Salt Lake City were used by wagon trains on their way to California, particularly during the 1849 gold rush. Mineral deposits were discovered in the nearby mountains by Union soldiers in the early 1860s (Ellsworth, 1985). A smelter was built in the valley and rail spurs were extended north to the transcontinental railroad at Ogden. Commerce, mining, and transportation transformed the pioneer settlement into a regional urban center within two decades of its founding.

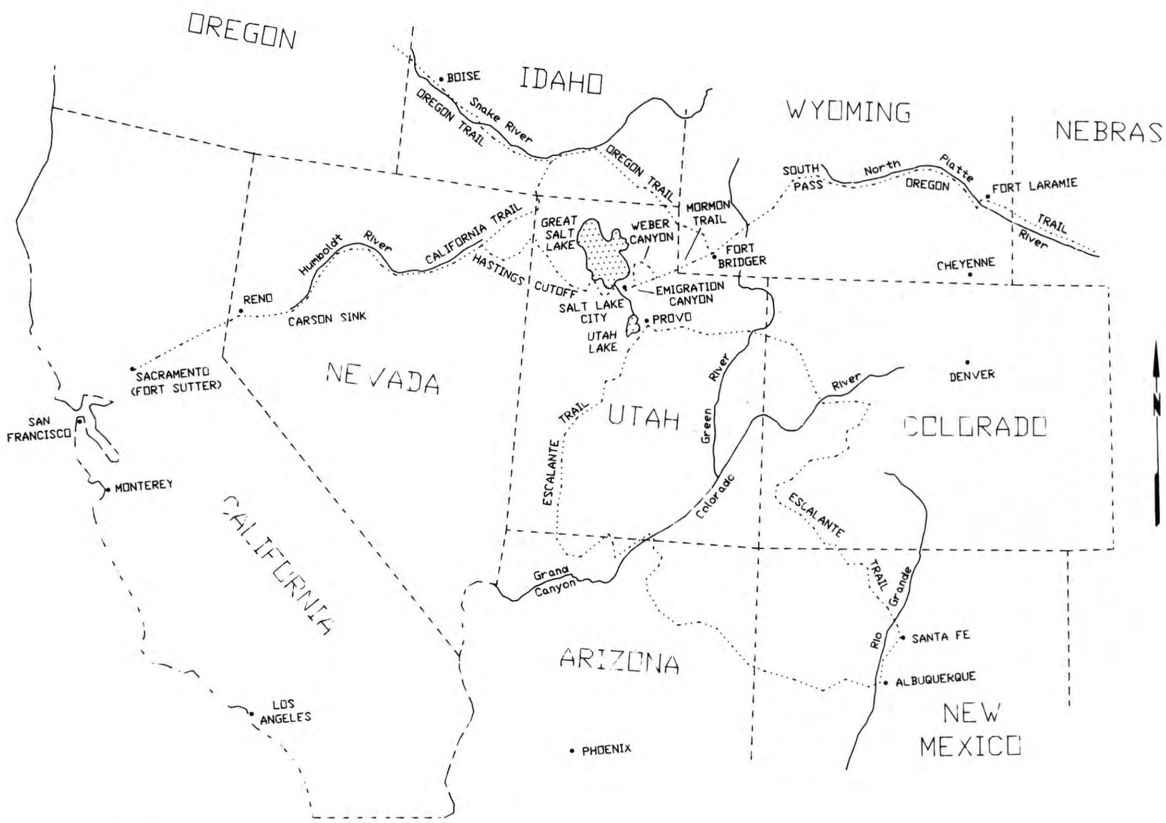



*Figure 2. Historic trails important to the founding and development of Salt Lake City (modified from Miller, 1968; Smart, 1988).*

## GEOLOGICAL FACTORS INFLUENCING FOUNDING AND DEVELOPMENT

The Mormons founded Salt Lake City as a religious center hoping that its isolation would allow them to practice their religion with minimum interference. The valley was protected by narrow canyons and high, steep mountains to the east and deserts to the west. The main immigration routes to the west were the Oregon and California Trails far to the north of the Salt Lake Valley (figure 2).

The journal of Orson Pratt, one of the advance scouts of the Pioneer Company, records the following impression of the Salt Lake Valley and its natural resources (Ellsworth, 1985):

*"July 22nd, 1847...After going down into the valley about 5 miles, we turned our course to the north, down towards the Salt Lake. For 3 or 4 miles north we found the soil of a most excellent quality. Streams from the mountains and springs were very abundant, the water excellent, and generally with gravel bottoms. A great variety of green grass, and very luxuriant, covered the bottoms for miles where the soil was sufficiently damp, but in other places, although the soil was good, yet the grass had nearly dried up for want of moisture. We found the drier places swarming with very large crickets, about the size of a man's thumb [Mormon Crickets]. This valley is surrounded with mountains, except on the north: the tops of some of the highest being covered with snow. Every 1 or 2 miles streams were emptying into it from the mountains on the east, many of which were sufficiently large to carry mills and other machinery. As we proceeded towards the Salt Lake the soil began to assume a more sterile appearance, being probably at some seasons of the year overflowed with water. We found as we proceeded on, great numbers of hot springs issuing from near the base of the mountains."*

Although much different from the environment they left behind in the east, the Salt Lake Valley provided the Mormon pioneers with sufficient natural resources of water, soil, and building materials to establish a permanent settlement. Abundant precipitation in the Wasatch Range ensured a perennial source of water in streams entering the valley and for springs on the valley floor. Many of the streams had sufficient discharge to power sawmills. Irrigation works could be easily constructed at the mouths of canyons to serve fields in low-lying valley areas (Harris, 1941). The dry "Indian Summer" of September proved to be beneficial during harvest time. Lacustrine and alluvial soils consisting chiefly of well-drained, gravelly, silty sand were arable for a wide variety of crops. Adequate quantities of construction materials including trees, sandstone, granite, sand, gravel, and refractory clay were readily available in the vicinity.

## EXPLANATION

### DESCRIPTION OF MAP UNITS

Quaternary and Recent Deposits:

- **Qa** — Alluvial Deposits — *Stream alluvium, existing and abandoned flood plains, alluvial fans, and local mudflows.*
- **Qfpd** — Flood-plain and Delta Complex — *Chiefly fine-grained and poorly drained sediments; includes deposits from the Jordan River and Great Salt Lake.*
- **Qm** — Glacial Moraines and Talus — *Moraines, till, and outwash deposits consisting of unsorted mixtures of clay, silt, sand, gravel, and boulders; talus accumulations at the base of steep slopes or cliffs.*
- **Qlb** — Provo-level and Younger Lake Bottom Sediments — *Clays, silts, sands, and locally offshore sand bars.*
- **Qpsf** — Provo-level and Younger Shore Facies — *Chiefly sand and gravel in beach deposits, bars, spits, and deltas.*
- **Qb** — Bonneville-level Shore Facies — *Chiefly sand and gravel in beach deposits, bars, spits, and deltas.*
- **T-Qa** — Harkers Alluvium — *Unconsolidated and poorly sorted boulders, gravel, sand, silt, and clay deposited in pre-Lake Bonneville alluvial fans.*
- **Tsu** — Tertiary Sedimentary Rock Units, *undifferentiated.*
- **Tvu** — Tertiary Volcanic Rock Units, *undifferentiated.*
- **Tpu** — Tertiary Plutonic Rock Units, *undifferentiated.*
- **Mu** — Mesozoic Rock Units, *undifferentiated.*
- **Pu** — Paleozoic Rock Units, *undifferentiated.*
- **P€** — Precambrian Rock Units, *undifferentiated.*

### MAP SYMBOLS

Contact Between Units.

Suspected or known Quaternary faults — dashed where approximately located, dotted where concealed, queried where suspected; bar and ball on downthrown side.

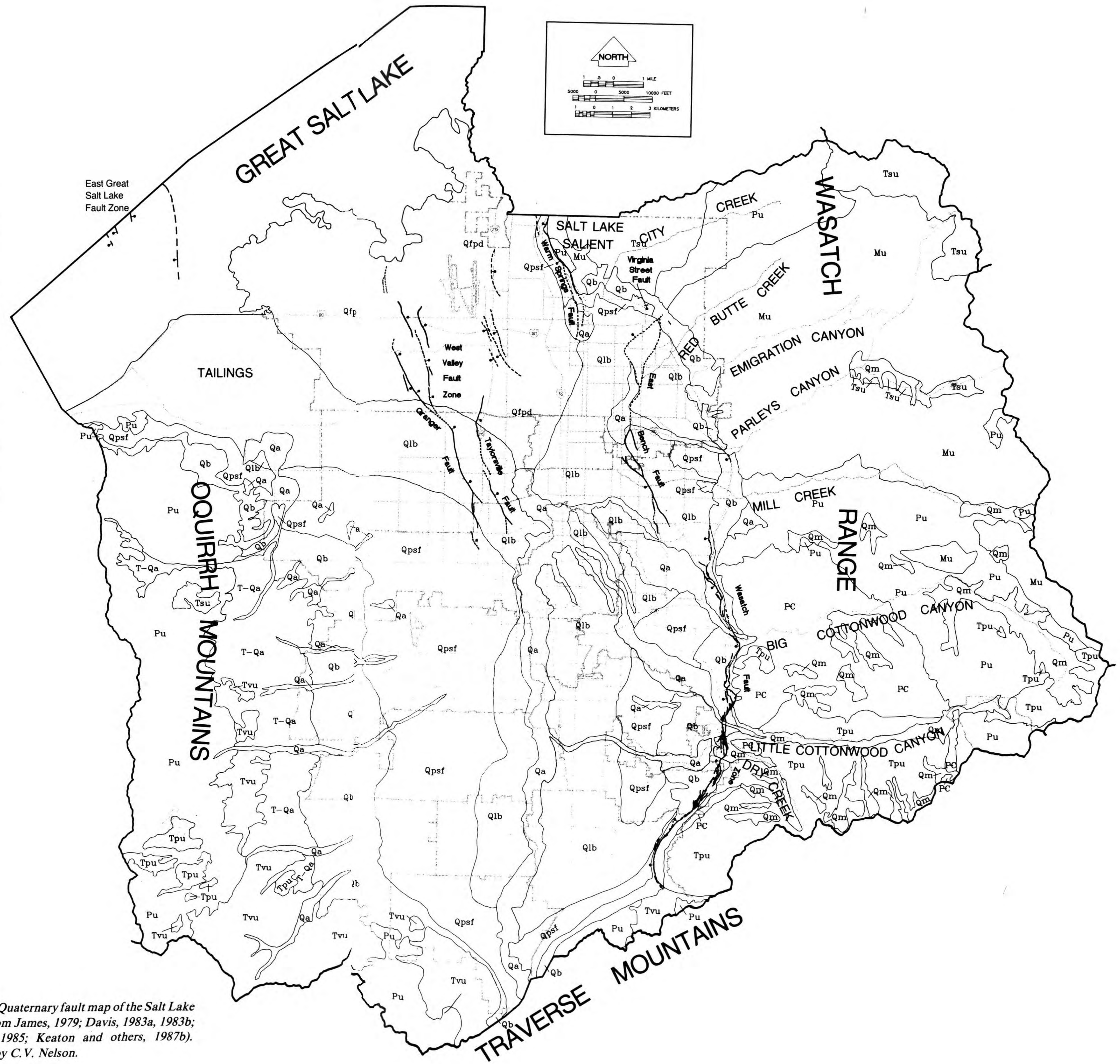



*Figure 3. Generalized geology and Quaternary fault map of the Salt Lake City metropolitan area (compiled from James, 1979; Davis, 1983a, 1983b; Klauk, 1984; Scott and Schroba, 1985; Keaton and others, 1987b). Compiled by K.M. Harty, digitized by C.V. Nelson.*

# GEOLOGIC SETTING

*Suzanne Hecker and Kimm M. Harty*

## REGIONAL GEOLOGY

Salt Lake City lies above a deep, sediment-filled, structural basin of Cenozoic age that is flanked by two uplifted range blocks, the Wasatch Range and the Oquirrh Mountains. The Wasatch Range is the easternmost expression of pronounced Basin and Range extension in north-central Utah. It is bounded on the west by a major, active zone of normal faulting (the Wasatch fault zone) that traverses the Salt Lake City metropolitan area (figure 3). East of the city in the Wasatch Range, outcrops of sedimentary, metamorphic, and igneous rocks of Precambrian through Tertiary age (figure 3) record a succession of settings along a recurrent tectonic trend.

Salt Lake City is located near the junction of two of western North America's most prominent and persistent structural elements: the Wasatch line and the Uinta arch (figure 4). Both alignments existed as early as the late Precambrian and continue to exert an influence on geologic events. Originally defined as the eastern boundary of the Cordilleran geosyncline by Kay (1951), the Wasatch line has since been used to delineate similar north-south trends along the eastern margins of Mesozoic thrusting and Cenozoic block faulting in western North America. The present Wasatch line is represented by the Wasatch and Sevier fault zones (figure 5), which trend north-northeastward through the state and separate the Basin and Range physiographic province from the Middle Rocky Mountains and Colorado Plateau physiographic provinces (figure 4). The Uinta arch, which includes the present-day Uinta Mountains in northeastern Utah, is an east-trending anticlinal structure with a history of repeated uplift along the axis of a late Precambrian, sediment-filled structural trough. The Uinta arch intersects the Wasatch line at nearly right angles (figure 4) and acted as a buttress against sedimentation and eastward-directed tectonism throughout much of Phanerozoic time. The following summary of the region's geologic history and bedrock geology is based on the work of numerous investigators. For more information, the reader is referred to Crittenden (1964, 1977), Hill (1977), Miller and others (1983), Stokes (1986), and Hintze (1988).

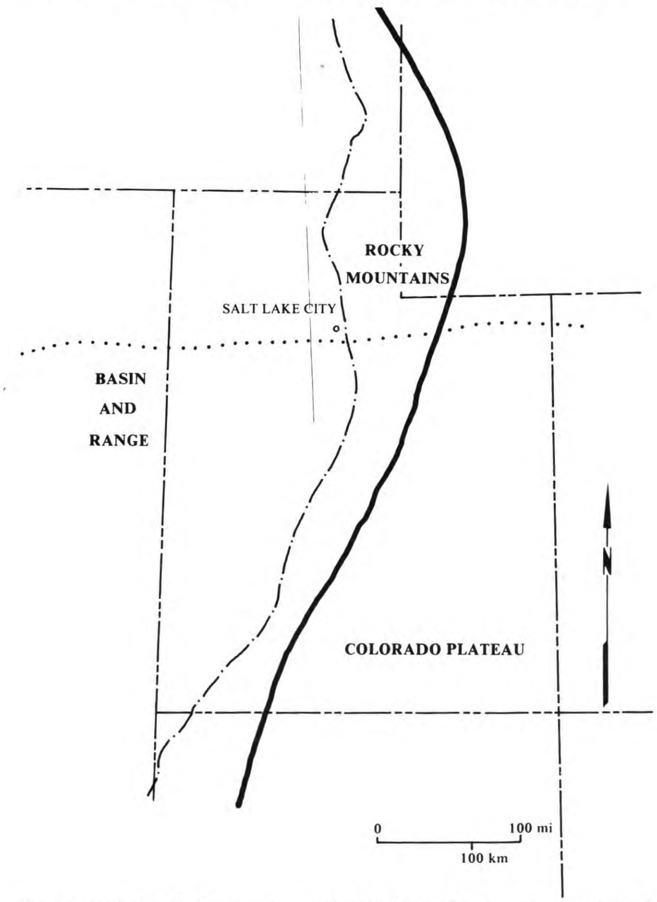



*Figure 4. Tectonic lineaments and physiographic provinces of Utah. Solid line is Wasatch line as originally defined by Kay (1951); dot-dash line is the eastern boundary of the Basin and Range physiographic province (also present day interpretation of the Wasatch line); dotted line shows the approximate axis of the Uinta arch (modified from Stokes, 1977).*

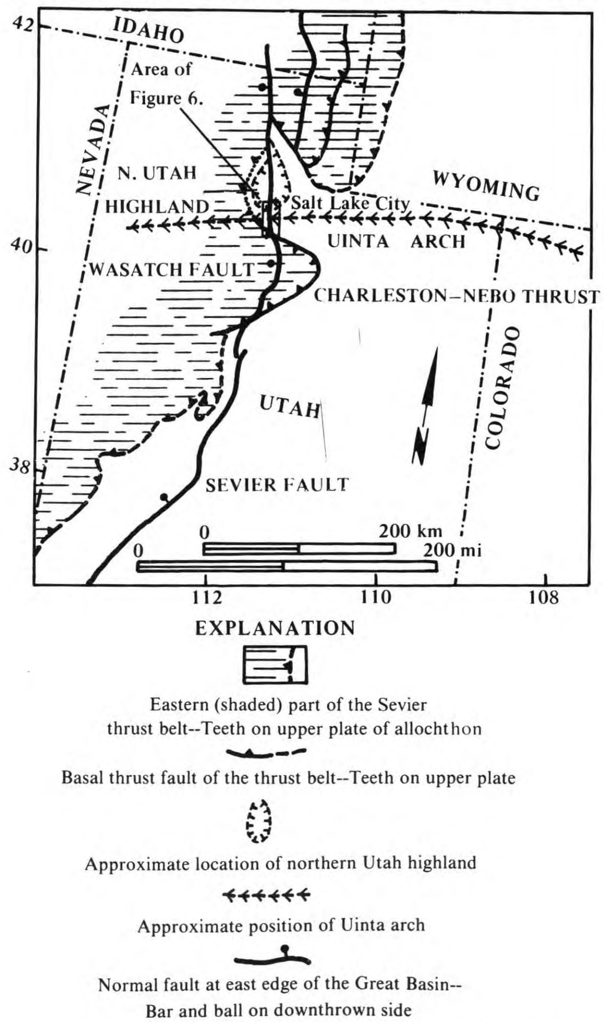



*Figure 5. Location of the foreland of the Sevier thrust belt with respect to other tectonic elements in Utah (the Uinta arch, northern Utah highland, and the Wasatch fault zone). Area in box is shown in figure 6 (modified from Tooker, 1983).*

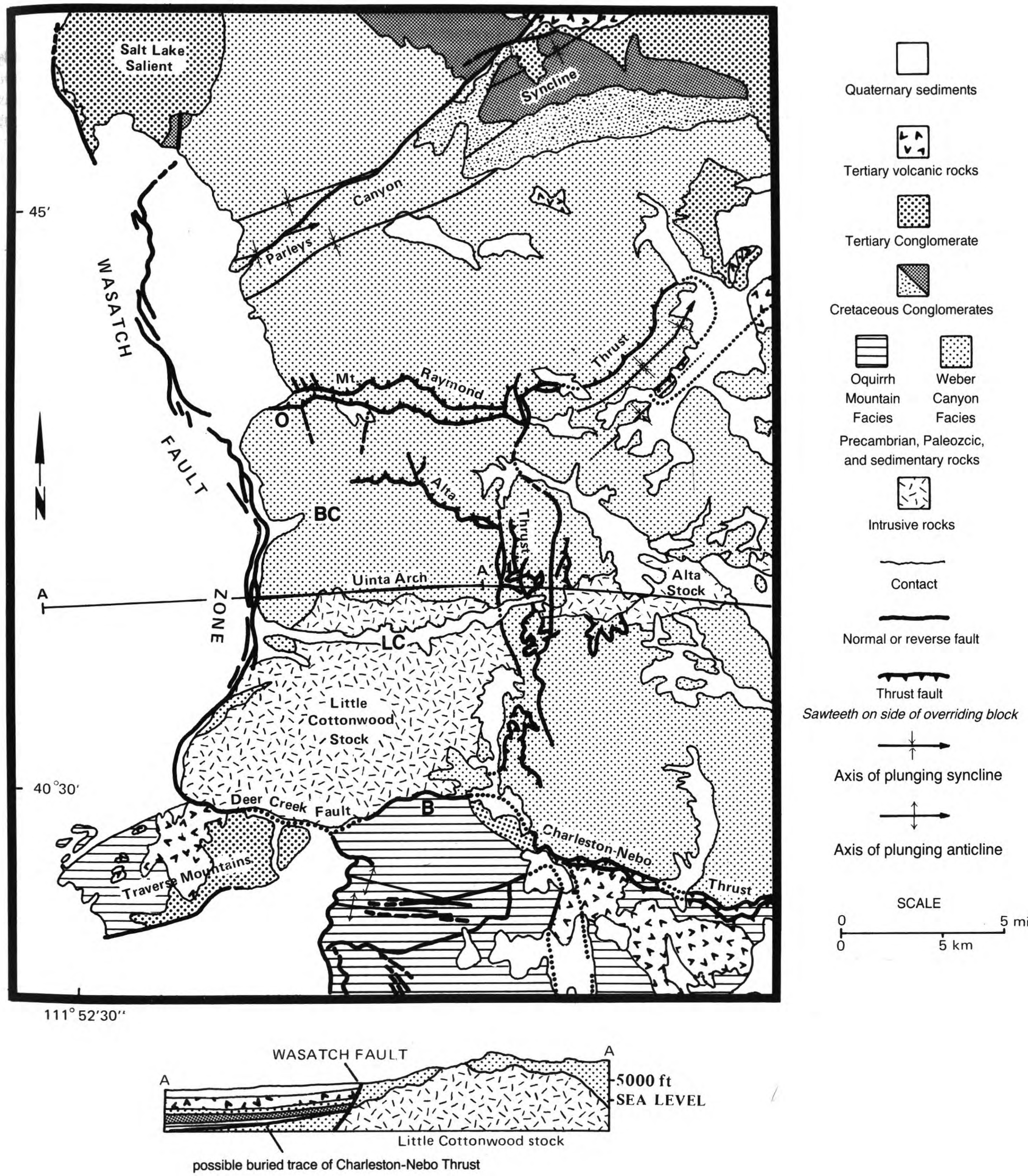



***Figure 6.** Generalized structure of the central Wasatch Range east of Salt Lake City; O-Mt. Olympus, B-Box Elder Peak, BC-Big Cottonwood Canyon, LC-Little Cottonwood Canyon (modified from Crittenden, 1964).*

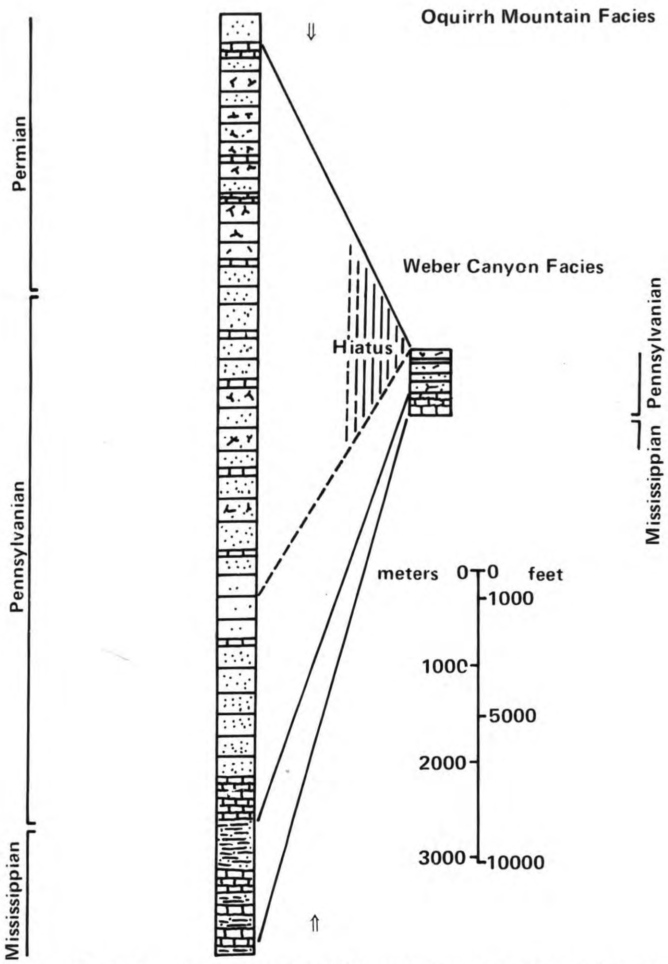



*Figure 7.* *Contrast in stratigraphic thickness between late Paleozoic rocks deposited on the shelf (Weber Canyon facies) and in the Cordilleran miogeocline (Oquirrh Mountain facies). Arrows indicate location of Charleston-Nebo thrust fault (modified from Crittenden, 1977).*

The Wasatch line as originally defined was preceded by a similarly aligned continental rift margin formed during the breakup of the North American craton during the late Precambrian Era. Initial detrital deposition was gradually replaced by carbonate shelf sedimentation as the shoreline migrated eastward. The Cordilleran geosyncline was well developed by Cambrian time, and shallow marine conditions, with deposition of calcareous ooze, continued throughout much of the Paleozoic Era. However, episodic uplift along the Uinta arch precluded deposition or caused erosion of Ordovician, Silurian, and Devonian sedimentary strata. As a result, the Wasatch line, as defined by the thickness of Paleozoic rocks, makes a westward bend around the Salt Lake City region.

Classic geosynclinal development was disrupted in late Mississippian through Permian time by the Antler and subsequent smaller orogenies at the western margin of the miogeosyncline in central Nevada. Sedimentation patterns shifted as the orogenic highlands, together with emergent cratonic terrains to the east, contributed clastic debris to ongoing carbonate shelf sedimentation in north-central Utah. During the Triassic and Jurassic Periods, the region was characterized by marginal marine conditions of alternating subaerial and marine deposition.

Beginning in Late Jurassic time, the Sevier and Laramide orogenies brought to a close the long period of basin filling in north-central Utah. The Cordilleran geosyncline was tectonically shortened and deformed into thin-skinned, low-angle fold and thrust sheets that were driven eastward along stratigraphic zones of weakness. The leading edge of the thrust belt was driven up along the eastward-thinning, west-dipping layers of the miogeosyncline and came to a halt along the edge of the cratonic shelf (the Wasatch line). In north-central Utah, the structurally high Uinta arch and nearby northern Utah highland impeded the advance of thrusting and created a reentrant in the thrust belt foreland around Salt Lake City (figure 5). Major thrust sheets are exposed in the Wasatch Range east and south of Salt Lake City (Charleston-Nebo thrust, Alta thrust, Mt. Raymond thrust; figure 6) and in the Oquirrh Mountains west of the Salt Lake Valley. The transported sections of sediment were originally deposited tens of miles to the west in a rapidly subsiding late Paleozoic basin and are now many times thicker than their shelf-deposited counterparts in the Wasatch Range east of the city (figure 7). The Laramide orogeny, which began at the close of the Mesozoic Era, continued folding and thrusting within the Sevier orogenic belt and initiated basement block uplifts to the east of the Wasatch line. Renewed, strong deformation along the Uinta arch produced the modern Uinta Mountains and caused uplift and folding in adjacent portions of the central Wasatch Range, creating the Parleys Canyon syncline (figure 6).

The Laramide orogeny ended abruptly in the mid-Eocene with a major shift in the regional stress regime. A change from compressional to extensional tectonics was accompanied by widespread igneous activity. Voluminous ash flows and other volcanic rocks covered large areas in and southwest of the Salt Lake City region, and the structurally weakened Uinta arch provided pathways for intrusion of molten material near the Wasatch line (Little Cottonwood and Alta stocks; figure 6). By Miocene time, large amounts of east-west extension and crustal thinning were being accommodated on closely-spaced, low-angle normal faults in the eroded highlands of the Sevier orogenic belt.

Since about 10 million years ago, thin-skinned extension has been succeeded by deeper-seated Basin and Range-style faulting which is responsible for the tilted, north-trending, horst-and-graben structures that define the modern physiography. The eastern margin of the Basin and Range physiographic province (the modern Wasatch line) has generally corresponded with the region's inherited zone of tectonic discontinuity. However, the Wasatch fault zone cuts a nearly linear path across the Uinta arch and northern Utah highland, rather than following the path of prior tectonic response westward around the Salt Lake City area (figure 5). In detail, the Wasatch fault zone does form a salient at the Traverse Mountains, where the Precambrian rocks of the Uinta arch and the Charleston-Nebo thrust converge with the margins of the Little Cottonwood stock (figure 6). The Traverse Mountains form a spur that extends between the Wasatch Range and the Oquirrh Mountains and defines the south end of the Salt Lake Valley graben. A general isopach map of the unconsolidated and semi-consolidated sediments in the valley, derived from drill hole and geophysical data (Mattick, 1970), indicates that nearly 0.5 miles (0.8 km) of material has accumulated in the deepest part of the structural trough since subsidence began in middle or late Tertiary time. Basin-fill thickness and mountain range height together record a minimum vertical displacement of 2 miles (3.2 km) across the Wasatch fault zone. However, little is known about the distribution and configuration of subsurface faults, the configuration of the graben, or the nature of deep sediments underneath the Salt Lake Valley.

## BEDROCK GEOLOGY

Rocks and structures of great diversity are exposed along the range fronts and canyons flanking the Salt Lake Valley. Rocks that crop out in the Wasatch Range include Tertiary and Cretaceous conglomerates, Triassic and Jurassic redbeds, a Precambrian diamictite, and billion-year-old sediments that are locally metamorphosed by an igneous intrusion (Little Cottonwood stock; figures 3 and 6) that is several tens of millions of years old. Limestone, quartzite, sandstone, and shale, encompassing a range of deformational histories, are all folded into a broad, northeast-plunging synclinorium (Parleys Canyon syncline; figure 6) that has been displaced across the Wasatch fault zone. Strikingly different geology is exposed across the valley in the Oquirrh Mountains, which are comprised of complexly folded and faulted upper Paleozoic quartzite, sandstone, and carbonates.

Upper Precambrian clastics form the lower part of Big Cottonwood Canyon (figure 3) and the steep Wasatch Range front near the south end of the valley. These interbedded shales and quartzites have been essentially unaffected by regional metamorphism and commonly show preservation of sedimentary features. In contrast, older Precambrian rocks which crop out at the range front north of Little Cottonwood Canyon (figure 3) have been strongly folded, intruded, and recrystallized into schists and gneissic quartzites.

Upper Paleozoic strata are extensively exposed in the Oquirrh Mountains (figure 3), but rocks spanning most of Paleozoic time crop out in just two areas east of Salt Lake City in the Wasatch Range (figure 3). In the Wasatch Range, a generally fining upward sequence of Cambrian quartzite, shale, and limestone are separated from a series of mainly Mississippian fossiliferous carbonates by an unconformity and associated coarse clastics. In contrast, the Oquirrh Mountains consist almost entirely of Upper Mississippian to Lower Permian sediments. The extraordinary thickness of the interbedded limestone, sandstone, and quartzite in the Oquirrh Mountains is up to 10-15 times greater than contemporaneous deposits exposed in the Wasatch Range (figure 7).

Relatively erodible Mesozoic rocks form the subdued range front just east of Salt Lake City between Mill Creek and Red Butte Canyons (figure 3). Triassic, Jurassic, and Cretaceous limestone and redbeds have been tightly folded into the anticlinal core of the range-front synclinorium. Upper Cretaceous and Eocene coarse conglomerates show progressively less folding. Nearly horizontal conglomerates cap tectonically deformed and eroded Paleozoic and Mesozoic strata in the Salt Lake salient (figures 3 and 6) and farther east in the Wasatch Range.

Late Eocene and Oligocene igneous activity is represented by large intrusions of quartz monzonite (Little Cottonwood stock, 24-31 m.y. BP; Alta stock, 32-33 m.y. BP) exposed in steep, glaciated Wasatch Range canyons (figures 3 and 6), and by several smaller igneous bodies aligned along the east-trending Uinta arch at the southern end of the valley. The intrusives are associated with extensive zones of mineralization that are the basis for several rich mining districts in the area. Other igneous rocks (latite-andesite volcanics) of similar age are exposed in the Oquirrh Mountains and Traverse Mountains and locally elsewhere in and around the Salt Lake Valley (figures 3 and 6). Upper Tertiary sediments, deposited after the onset of Basin and Range faulting, are buried beneath younger basin fill in the Salt Lake Valley.

## QUATERNARY GEOLOGY

### Surficial Deposits

The near-surface and surficial geology of the Salt Lake Valley is dominated by Quaternary materials deposited within the last 30,000 years by Lake Bonneville (about 30,000-14,000 yr BP; figure 8). The lake's basin has been an area of closed drainage for much of the past 15 million years, and several lakes, some possibly similar in size to Lake Bonneville (19,800 miles$^2$; 51,300 km$^2$) existed in the basin during this time (Scott, 1988a). Shorelines of Lake Bonneville are prominent features in the Salt Lake Valley and other valleys in western Utah. The lake reached a maximum elevation of about 5092 feet (1552 m) (Currey and James, 1982) and a maximum depth of about 1150 feet (351 m) (Currey, 1980). Deposition and reworking of sediments during Lake Bonneville time obscured most evidence of previous lake cycles as well as interlacustrine geomorphic features. Because of this, the late Pleistocene and Holocene history of the Salt Lake Valley is well documented relative to that prior to Lake Bonneville time.

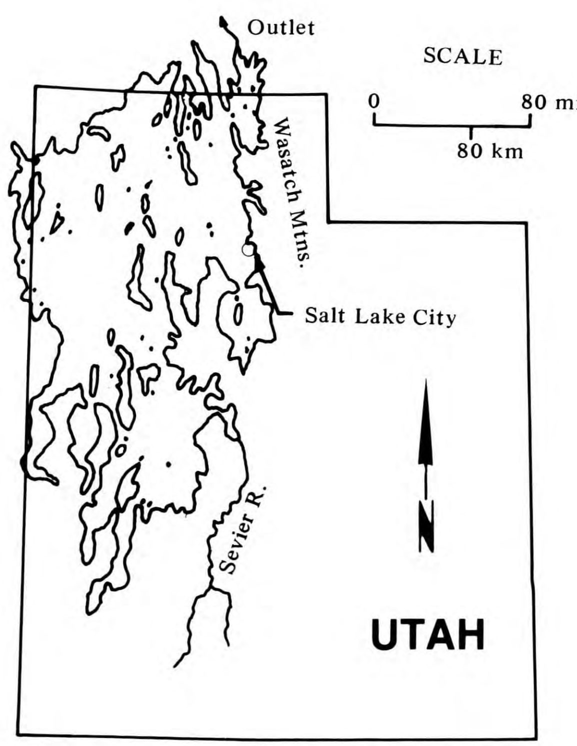



***Figure 8.*** *Maximum extent of Lake Bonneville in late Pleistocene time (modified from Stokes, 1986).*

**Pre-Lake Bonneville deposits —** Evidence of geologic processes active in the Salt Lake Valley prior to 30,000 yr BP is scant, but stratigraphic exposures and limited sediment coring suggest that the valley has been aggrading under a variety of depositional environments, including semi-arid, alluvial-fan deposition and more humid lacustral and glacial deposition. Paleomagnetic dating and stratigraphic evidence of soil-forming sequences obtained from deep core samples taken near the Great Salt Lake show that as many as 28 lakes, most of them small, may have existed at that location during the past 800,000 years (Eardley and others, 1973). The subsurface boundary between the generally unconsolidated Quaternary deposits and underlying consolidated Tertiary deposits and bedrock strata has not been firmly established in most parts of the Salt Lake City region (Mabey, 1987). In the Salt Lake Valley, Quaternary deposits are estimated to reach a maximum thickness of about 2300 feet (700 m)(Arnow and Mattick, 1968; Arnow and others, 1970; Van Horn, 1981). The deposits generally thin toward the south end of valley and are thinnest along mountain fronts (Arnow and others, 1970).

Early in the Quaternary, the Salt Lake Valley is believed to have undergone widespread alluvial-fan deposition, possibly accelerated by large-scale, normal faulting along mountain fronts (Eardley, 1955). Evidence of these semi-arid depositional processes can be seen along the flanks of the Oquirrh Mountains, where the dominant rock unit is the uplifted Harkers Alluvium (T-Qa; figure 3). This unit consists of moderately to well-consolidated, poorly sorted, silt- to boulder-size material that once formed a series of coalescing alluvial fans greater than 300 feet (91 m) thick (Slenz, 1955). Sometime during the early Pleistocene, fan deposition ceased and was replaced by a period of intense degradation, including fan erosion, pedimentation, and pediment dissection, possibly due to a more humid environment and cessation of faulting (Eardley, 1955). Late Pliocene or early Quaternary materials, including the Harkers Alluvium, appear to be buried beneath pre-Lake Bonneville lacustrine sediments in the valley (Lofgren, 1947; Slenz, 1955; Feth and others, 1966).

Pre-Lake Bonneville lacustrine sediments have been found locally in northern Utah, including the Salt Lake Valley (Scott, 1988a). Recent aminostratigraphic dating of mollusk shells in these deposits has led to the identification of three middle Quaternary, deep-lake cycles in the Salt Lake City region that pre-date Lake Bonneville (McCoy, 1987). These include an unnamed cycle that just pre-dates Lava Creek (Pearlette "O") ash deposited about 600,000 yr BP, the Pokes Point lake cycle of about 200,000 yr BP (McCoy, 1987), and the Little Valley lake cycle that dates from about 150,000 to 130,000 yr BP (Scott and others, 1983). In addition, a minor lake cycle, the Cutler Dam cycle of between 65,000 and 40,000 yr BP, has been identified by Oviatt and others (1985). Deposits of the Little Valley and Cutler Dam lake cycles have been identified in shallow borings in the Salt Lake Valley by Keaton and others (1987a).

Shore-deposit elevations of these former lakes indicate that each was smaller than Lake Bonneville. Lacustrine deposits thought to belong to the unnamed lake cycle of about 600,000 yr BP have been found in the southern part of the Salt Lake Valley near the Jordan River, and at an elevation of 4659 feet (1420 m) in a gravel pit about 50 miles (80 km) northwest of Salt Lake City (McCoy, 1987). Pokes Point and Little Valley deposits were identified at an elevation of 4685 feet (1428 m) in the same gravel pit. Little Valley sediments have also been found in a gravel pit in northern Salt Lake City, possibly north of the mouth of Big Cottonwood Canyon, and along Parleys Creek (Scott and Shroba, 1985). The highest known elevation of the Little Valley lake cycle is 4888 feet (1490 m), about 245 to 395 feet (75-120 m) below the highest shoreline of Lake Bonneville (Scott and others, 1983). Possible Little Valley deposits have been found as high as 4987 to 5003 feet (1520-1525 m), but have been uplifted above their original elevation by later faulting (McCoy, 1987). Unfaulted, suspected Little Valley sediments have recently been discovered south of Salt Lake City near the Traverse Mountains at an elevation of 4954 feet (1510 m) and may represent the highest level attained by this lake cycle (McCoy, 1987). Cutler Dam lacustrine sediments have been identified in extreme northern Utah, and this lake cycle is thought to have reached no higher than 4400 feet (1341 m) (Oviatt, 1986; Oviatt and McCoy, 1988).

Pre-Lake Bonneville glacial deposits have been mapped in the Salt Lake City area. Glacial till, locally termed the Dry Creek till (Madsen and Currey, 1979) is present at the mouths of Little Cottonwood and Bells Canyons in the Wasatch Range (figure 3). Based on weathering characteristics, the till is estimated to have been deposited during oxygen isotope stage 6, or about 150,000 yr BP and is believed to be correlative with the Bull Lake glaciation of Wyoming's Wind River Range (Madsen and Currey, 1979; Scott and Shroba, 1985; Scott, 1988b). Outwash from this glacial advance is exposed along Dry Creek and in gravel pits near the mouth of Big Cottonwood Canyon where it overlays Little Valley lake sediments (Scott and others, 1983; Scott, 1988b). It has been suggested that the Little Valley lake cycle may have been contemporaneous with a younger stage of the Dry Creek glacial advance (Scott and others, 1983; Scott, 1988b).

Aside from a few short wet intervals, the period between the Little Valley lake cycle and the beginning of the Bonneville lake cycle (about 130,000-30,000 yr BP) represented an interlacustral environment, characterized by soil formation, landscape incision, and deposition of colluvium, alluvium, loess, and eolian sand (Scott and others, 1983).

**Lake Bonneville and post-Lake Bonneville deposits —** Most researchers agree that the Bonneville lake cycle began between 30,000 and 25,000 yr BP and was approximately contemporaneous with the last glacial maximum in the Rocky Mountains (Scott, 1988b). Referred to in the Wasatch Range as the Bells Canyon glacial advance, it is broadly equivalent in age to the Pinedale glaciation of the Wind River Range (Currey and others, 1983; Scott and Shroba, 1985). Glacial moraines overlying older till of the Dry Creek advance extend about 0.6 miles (1 km) into the Salt Lake Valley from the mouths of U-shaped Little Cottonwood (figure 9) and Bells Canyons (figure 3) and are estimated to have been deposited 19,000 to 20,000 yr BP (Madsen and Currey, 1979). Besides lateral and terminal moraines, glacial deposits of this age consist of outwash and ablation till (Davis, 1983a). Scott and Shroba (1985) estimate that the Bells Canyon till was deposited prior to 22,000 yr BP, while Lake Bonneville was rising, but still at a low or intermediate stage.

Between 21,000 and 20,000 yr BP, the transgressing lake oscillated near an elevation of 4468 feet (1362 m), forming the Stansbury shoreline (Currey and others, 1984; Green and Currey, 1988). The lake reached its maximum elevation of about 5092 feet (1552 m) approximately 15,300 yr BP. At that elevation, the lake found an outlet in the Zenda-Red Rock Pass area of southern Idaho and flowed northward into the Snake River drainage. Catastrophic failure of unconsolidated deposits at the outlet channel occurred about 14,500 yr BP, and within a matter of a few weeks lowered the lake more than 300 feet (91 m) to the Provo level (about 4740 feet; 1445 m)(Currey and others, 1984; Scott and Shroba, 1985). It is estimated that the Bonneville flood released approximately 35-40 million feet$^3$/sec (1.0-1.1 million m$^3$/sec) of water into the Snake and Columbia River drainages (Malde, 1985; Jarrett and Malde, 1987).

***Figure 9.*** *Little Cottonwood Canyon in the Wasatch Range showing U-shaped valley profile resulting from glacial erosion. View is to the west toward the Salt Lake Valley (photograph credit, W.R. Lund).*

Lowering of Lake Bonneville below the Provo level began about 14,000 yr BP, and is believed to have been due to climatic changes which caused evaporation to exceed water input to the lake (Scott and Shroba, 1985). By about 12,000 yr BP, Lake Bonneville had regressed to at least as low as the lowest historic level of the Great Salt Lake. The lake then experienced a brief transgression between 11,000 and 10,000 yr BP to the Gilbert level (about 4250 feet; 1295 m) before receding to and remaining within about 20 feet (6 m) of its historic average level. It is estimated that deglaciation of the upper reaches of Little Cottonwood and Bells Canyons began no later than 13,000 yr BP and was completed before 8000 yr BP (Madsen and Currey, 1979).

Following the drop of Lake Bonneville from the Bonneville shoreline, and again as the lake receded from the Provo shoreline, streams began to regrade to newly created base levels. Large fan-delta complexes at the mouths of major Wasatch Range canyons became deeply incised and the eroded material was deposited in the basin as a series of recessional deltas and alluvial fans. Fine-grained, deep-water lake sediments exposed to the atmosphere were transported by the wind and deposited as a layer of loess over much of the Bonneville basin (Machette and others, 1987). Closer to the mountain front, smaller streams were depositing alluvial fans at canyon mouths. This period of intense alluvial-fan formation came to an end about 5000 to 4500 yr BP as the climate became progressively drier (Machette and others, 1987).

The majority of Quaternary deposits shown on the surficial geology map of the Salt Lake Valley (figure 3) consist of sediments deposited or reworked by Lake Bonneville. Coarse-grained Bonneville shore facies (Qb) consisting of sand and gravel are found along the fronts of the Wasatch Range and Traverse and Oquirrh Mountains between the Bonneville and Provo shorelines. The combination of wave action and stream deposition into the lake formed beaches, spits, bars, and large deltas at the mouths of canyons (Davis, 1983a, 1983b). Shore facies of the Provo level (Qpsf) lie at and below the Provo shoreline and are similar texturally and geomorphically to the Bonneville-level facies. Distal portions of the deltas at Big and Little Cottonwood Canyons are Provo-level deposits derived from canyon streams and from erosion and redeposition of Bonneville-level material (Currey, 1980). Toward the center of the valley, deep-water deposits of clay, silt, and fine sand (Qlb) predominate.

Deposits related to the same shoreline at different localities are found at different elevations in the Salt Lake City region. Within the Salt Lake Valley, the elevation of the Bonneville shoreline varies from 5161 to 5216 feet (1573-1590 m)(Van Horn, 1972; Currey, 1982). This variation is attributed to a combination of isostatic rebound as the lake lowered and post-lake faulting (Miller, 1980). Isostatic rebound was generally greater near the center of the Bonneville basin, west of Salt Lake City, than at the edges of the basin where water depths were shallower (Miller, 1980; Currey, 1982).

Alluvial and flood-plain deposits (Qa) and flood-plain/delta deposits (Qfpd) cover a large portion of the Salt Lake Valley. Flood-plain deposits exist along the Jordan River and several of its tributaries (City Creek, Big and Little Cottonwood Creeks, and Parleys Creek) where the streams have incised Lake Bonneville sediments (figure 3). Included in the alluvial category (Qa) are numerous, mainly Holocene, debris-flow and alluvial-fan deposits at the mouths of canyons. Some of the largest fans are along the northeast-facing flank of the Oquirrh Mountains and southeast of Salt Lake City between Mill Creek and Big Cottonwood Canyons (figure 3). The extensive flood-plain and delta complex (Qfpd) in the western portion of Salt Lake City and the northwestern portion of the Salt Lake Valley near the Great Salt Lake consists chiefly of fine-grained sediments deposited by the Jordan River and its tributaries. The area generally is marshy owing to poor drainage conditions (Davis, 1983a).

Quaternary glacial deposits (Qm) associated with the Dry Creek and Bells Canyon glacial advances are found at the mouths of Little Cottonwood and Bells Canyons. Talus (Qm) occurs in steep mountain valleys in the Wasatch Range and Oquirrh Mountains. Although not shown on figure 3, small talus deposits are locally common from the Bonneville shoreline to up-slope bedrock sources in the Wasatch Range and Oquirrh Mountains.

## Faulting

Geologic and geomorphic evidence shows that repeated, normal-slip surface faulting has occurred in northern Utah through late Pleistocene and Holocene time. Most of this activity has taken place on the 230-mile-long (370 km) Wasatch fault zone (WFZ). This active fault has been divided into a series of discrete segments (figure 10) on the basis of topographic, paleoseismic, geophysical, geodetic, and geomorphic evidence (Schwartz and Coppersmith, 1984; Machette and others, 1986, 1989). These segments are believed to rupture independently of each other (Schwartz and Coppersmith, 1984). The WFZ was initially divided into six segments (Schwartz and Coppersmith, 1984), but recent work has further subdivided the WFZ into as many as 10 main segments (Machette and others, 1989) with surface traces as much as 44 miles (70 km) in length (figure 10). The portion of the WFZ traversing the Salt Lake City metropolitan area is known as the Salt Lake City segment. The surface trace of this segment extends for 22.8 miles (36.7 km) along the eastern edge of the Salt Lake Valley from the Salt Lake salient on the north to the Traverse Mountains on the south (figure 3). In planimetric form, the fault zone is convex toward the east (figure 3) and generally follows the base of the Wasatch Range (Schwartz and Coppersmith, 1984). Interpretation of seismic-reflection profiles suggests that the subsurface configuration of the WFZ is complex, but that in general it dips about 50° to the west toward the Salt Lake Valley (Smith and Bruhn, 1984; Snay and others, 1984).

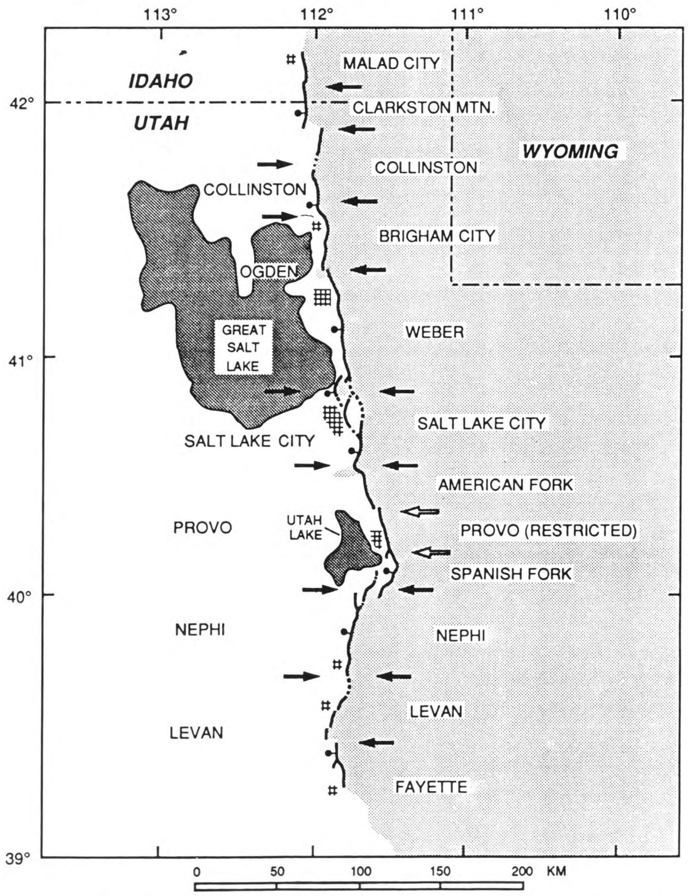



***Figure 10.*** *Segmentation of the Wasatch fault zone as proposed by Schwartz and Coppersmith (1984; left column) and Machette and others (1989; right column). Solid arrows indicate segment boundaries; hollow arrows show two segment boundaries proposed by Machette and others (1986) which probably are not persistent.*

At the ground surface, the Salt Lake City segment consists of steep, west-dipping (40° to 80°), *en echelon* and sub-parallel branch faults that form a zone of deformation as much as 1650 feet (500 m) wide (figure 3). Scarps, a few to as much as tens of feet high, are common, as are graben, horsts, and other structural and geomorphic features related to surface faulting. Near Little Cottonwood and Bells Canyons, lateral moraines of the Bells Canyon glacial advance have a stepped appearance resulting from multiple surface offsets on several fault traces (figure 11). At Dry Creek, about one mile (1.6 km) south of Bells Canyon, early and middle Holocene alluvial-fan deposits are offset by a greater amount than a late Holocene debris-flow levee, indicating that recurring surface faulting has taken place on the Salt Lake City segment during Holocene time (Lund and Schwartz, 1986). Grabens up to 650 feet (200 m) wide are present along the fault between Big and Little Cottonwood Canyons. A Provo-level delta at the mouth of Big Cottonwood Canyon is faulted extensively and backtilted. Delta surfaces which previously sloped westward now slope eastward in an area 650 to 1000 feet (200-305 m) wide immediately west of the fault (Scott and Shroba, 1985).

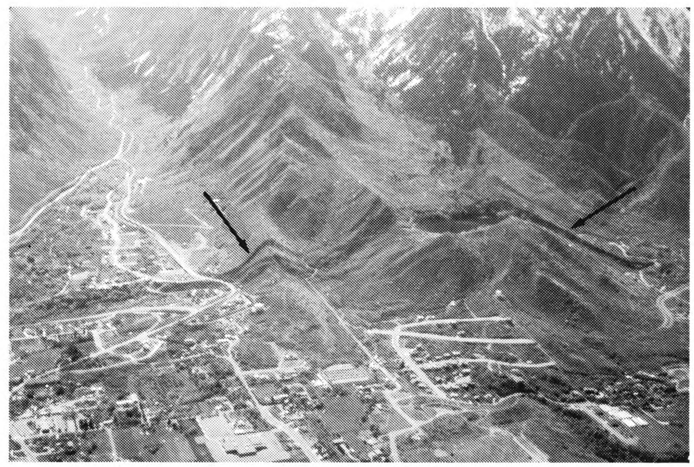


***Figure 11.*** *Oblique aerial view of the Wasatch fault zone at the mouth of Little Cottonwood Canyon (left) and Bells Canyon (right) southeast of Salt Lake City; note both the west-facing main scarps and east-facing antithetic scarps. Arrows indicate trace of the Wasatch fault zone where it offsets moraines (photograph credit, W.R. Lund).*

North of Big Cottonwood Canyon, the WFZ diverges to the northwest from the mountain front and passes through the eastern part of Salt Lake City (figure 3). This portion of the Salt Lake City segment is referred to as the East Bench fault, and its surface expression has been heavily modified by urbanization. Scarp heights along the northern section of the East Bench fault are a maximum of 165 feet (50 m) high and represent many surface-faulting events. Farther south, scarps on post-Lake Bonneville alluvium are as much as 36 feet (11 m) high.

The north extension of the Salt Lake City segment is referred to as the Warm Springs fault (figure 3). It is discontinuously exposed for about 3 miles (5 km) in quarry excavations on the west end of the Salt Lake salient. Most surficial deposits of Quaternary age have been removed from the quarries, producing several excellent exposures of bedrock along the fault plane (figure 12). Superimposed bedrock striations along the fault plane indicate at least two episodes of normal-slip movement (Pavlis and Smith, 1979). Pre-quarry observations by G.K. Gilbert (1890) record steep fault scarps with an estimated 40 feet (12 m) of post-Lake Bonneville displacement.

*Figure 12. The Wasatch fault zone exposed in bedrock at the west end of the Salt Lake salient (photograph credit, W.R. Lund).*

The Virginia Street fault, a short, east-west-trending, predominantly strike-slip fault, bounds part of the Salt Lake salient on its south side (figure 3). The fault is exposed for about 325 feet (100 m) in a quarry and, like the Warm Springs fault, shows evidence for two episodes of movement (Pavlis and Smith, 1979). Quaternary deposits in the quarry have been removed, and it is unclear how recently faulting occurred. Observations made prior to excavation of the quarry indicate that the fault deformed and offset possible Lake Bonneville sediments (Scott and Shroba, 1985).

There is no surface evidence of Quaternary faulting along the eastern base of the Oquirrh Mountains on the west side of the Salt Lake Valley. This implies that during Quaternary time the valley has been preferentially down-faulted along its eastern side. It has been suggested that the east-dipping West Valley fault zone (WVFZ), which trends discontinuously to the north-northwest for approximately 10 miles (15 km) in the central part of the valley (figure 3), may represent the current western boundary of the Salt Lake Valley graben (Cook and Berg, 1961; Marine and Price, 1964; Olig and others, 1986). Studies show that the fault zone, which consists of two subparallel main faults, the Taylorsville (eastern) and Granger (western) faults (figure 3), has been active numerous times during the late Quaternary (Olig and others, 1986; Keaton and others, 1987a).

Other known and suspected Quaternary faults traverse the area northwest of Salt Lake City beneath the Great Salt Lake. A series of northwest-trending normal faults, collectively termed the East Great Salt Lake fault zone, have been identified through Bouguer gravity surveys (Cook and others, 1966, 1980; Zoback, 1983) and seismic-reflection profiles (Mikulich and Smith, 1974; Viveiros, 1986). The zone consists of a main fault and numerous short, parallel, subsidiary faults all displaced down-to-the-west that extend beneath the Great Salt Lake (figure 3). Seismic-reflection data indicate that the main fault may be listric (Viveiros, 1986), and oil well data indicate that the main fault offsets Quaternary deposits beneath the lake (Pechmann and others, 1987). The East Lakeside Mountains fault zone (Cook and others, 1980), a major down-to-the-east fault, forms the western side of a large graben beneath the Great Salt Lake. It is a suspected Quaternary feature, but detailed information is not available.

## GROUND WATER

Ground water in the Salt Lake Valley occurs in late Tertiary and Quaternary alluvial and lacustrine basin-fill deposits that range from coarse gravel to clay. Four hydraulically connected aquifers have been identified in the basin sediments: 1) a deep, unconfined aquifer in gravelly deposits along the fronts of the Wasatch Range and Oquirrh Mountains; 2) a deep, confined aquifer in the center of the valley in gravel deposits beneath clay confining beds; 3) a shallow, unconfined aquifer in the center of the valley overlying the confined aquifer; and 4) local perched aquifers located primarily adjacent to mountain fronts (Hely and others, 1971a; figure 13). The deep, confined aquifer consists of discontinuous lenses of interbedded clay, silt, sand, and gravel up to 20 feet (6 m) thick and is the valley's principal aquifer. It thickens to the north and reaches a maximum thickness exceeding 1000 feet (305 m) (Hely and others, 1971a). The clay-rich confining layer separating the deep, confined aquifer from the overlying shallow, unconfined aquifer ranges in thickness from about 40 to 100 feet (12-30 m) and lies between 50 and 150 feet (15-46 m) below the ground surface (Hely and others, 1971a).

Recharge to the Salt Lake Valley ground-water system includes subsurface seepage through bedrock faults and fractures from surrounding mountains, subsurface flow from aquifers in Utah Valley draining into the topographically lower Salt Lake Valley, direct precipitation, infiltration of irrigation water, and seepage from streams, lakes, and canals. Intra-basin flow occurs between the various ground-water aquifers as shown in figure 13. The deep, unconfined aquifer is recharged by infiltration of water through coarse-grained deposits at the valley periphery and underflow from bedrock aquifers. Lateral flow from the deep, unconfined aquifer toward the valley center recharges the deep, confined aquifer, and the elevation of the potentiometric surface of this aquifer fluctuates with the amount of recharge received (Christenson, 1985). The shallow, unconfined and perched aquifers are recharged by direct precipitation, stream flow, and irrigation and canal seepage. The shallow, unconfined aquifer also receives water by upward migration through leaky confining beds overlying the deep, confined aquifer, whereas perched water moves downward into saturated zones or laterally into the adjacent shallow, unconfined aquifer (Hely, and others, 1971a; Klauk, 1984; Christenson, 1985). Regional movement of ground water is to the north, toward the Great Salt Lake.

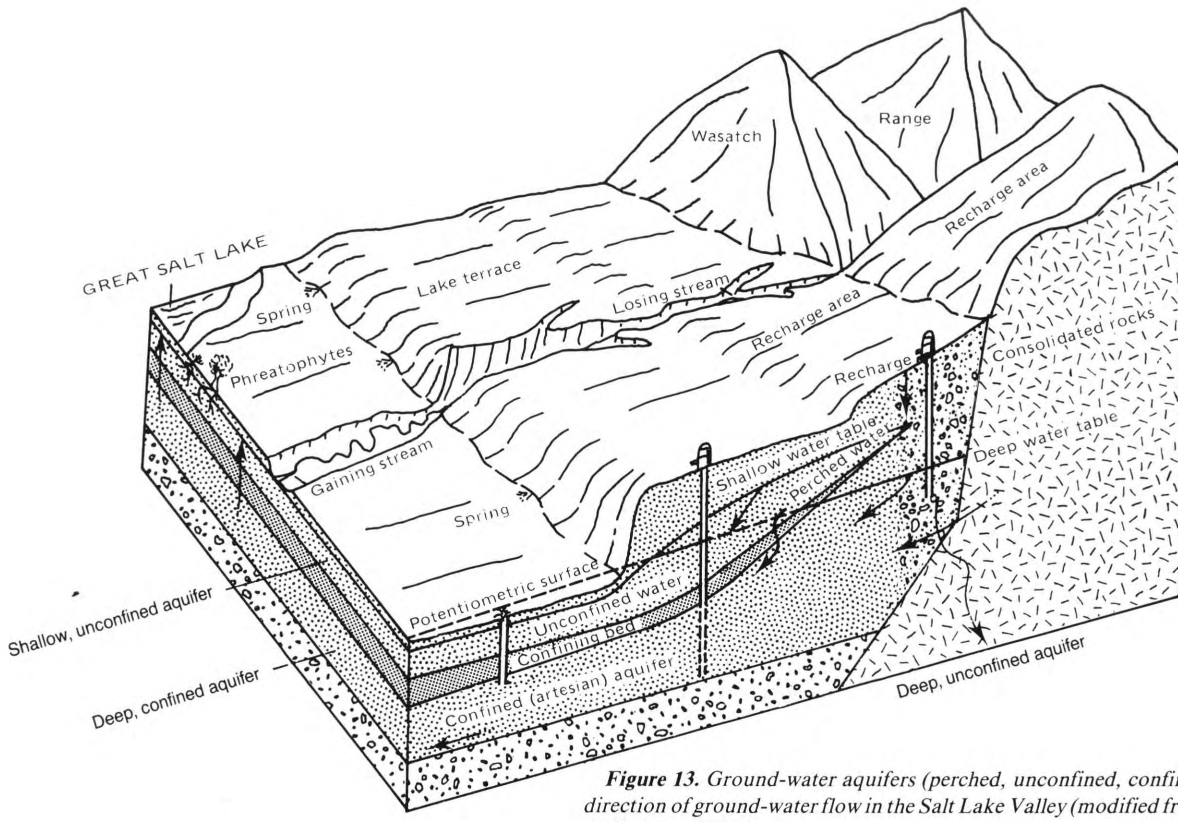



***Figure 13.*** *Ground-water aquifers (perched, unconfined, confined) and direction of ground-water flow in the Salt Lake Valley (modified from Hely and others, 1971a).*

## SEISMICITY

*William R. Lund*

Salt Lake City is near the center of the Intermountain seismic belt (ISB), a zone of concentrated earthquake activity extending from Arizona to northern Montana (figure 14) and historically one of the most seismically active areas in the continental United States (Smith and Sbar, 1974). Earthquakes in the ISB generally have shallow focal depths ($<10$ miles; $<16$ km) and usually show weak correlation with mapped geologic structures (Arabasz and others, 1987a). Three historic surface-faulting earthquakes have occurred in the ISB. They are the 1934 Hansel Valley, Utah earthquake ($M_S$ 6.6); the 1959 Hebgen Lake, Montana earthquake ($M_S$ 7.5); and the 1983 Borah Peak, Idaho earthquake ($M_S$ 7.3) (figure 14).

In Utah, the ISB follows a broad band of northerly trending normal faults, typically downfaulted to the west, that follow the boundary between the Basin and Range physiographic province and the Middle Rocky Mountains and Colorado Plateau physiographic provinces. The normal faulting developed in response to complex intraplate adjustments within the North American Plate, caused by west and northwest crustal extension. The WFZ is the largest and most active of these faults, exhibiting more than 36,000 feet (11,000 m) of vertical displacement during post-Oligocene time (Parry and Bruhn, 1987). The WFZ has been the source of repeated large-magnitude ($M \geq 7.0$) earthquakes during the Quaternary in the Salt Lake City region. However, other nearby faults have also been active during the Quaternary and represent additional seismogenic sources.

### HISTORICAL RECORD

The historical record of earthquakes in Utah effectively extends from 1850 with publication of the region's first newspaper. From 1850 through September 1989, more than 1000 felt events have been recorded in Utah with 152 having an estimated Richter magnitude ($M_L$) of 4 or greater (Arabasz and others, 1979b; Richins and others, 1981, 1984; Brown and others, 1986; Pechmann, 1989). Utah's two largest historic earthquakes are the 1901 Richfield earthquake ($M_L$ 6.5+) located 140 miles (225 km) south of Salt Lake City, and the 1934 Hansel Valley earthquake ($M_S$ 6.6) at the north end of the Great Salt Lake, 90 miles (145 km) north of Salt Lake City (figure 14). The Hansel Valley earthquake produced the only documented historic surface faulting in Utah, with a maximum vertical displacement of 20 inches (50 cm). Only two historic earthquakes in Utah of $M_L$ 5.5 or Modified Mercalli (MM) intensity VII or greater may have occurred on the WFZ. Due to uncertainty in their epicentral locations, they may also have occurred on nearby faults to the east or west of the WFZ (Arabasz and Smith, 1979; Arabasz and others, 1987a). Both events, a 1910 earthquake near Salt Lake City and a 1914 earthquake near Ogden (figure 14), had estimated magnitudes of $M_L$ 5.5.

The first seismograph in Utah was installed in 1907 on the University of Utah campus in Salt Lake City. Effective seismic monitoring did not begin until 1962 when the University established a regional seismic network (Arabasz, 1979). In 1974, the network was greatly expanded and telemetered. It now consists of 80 stations in Utah, Idaho, Wyoming, Montana, and Nevada (Pechmann, 1989).

Northern Utah is an area of high seismic activity (figure 15), much of which, upon cursory examination, appears to be associated with the WFZ. However, recent work by Arabasz and others (1987a) indicates that the WFZ may be largely aseismic, at least during the period for which good earthquake epicentral locations are available (1962 to present). Arabasz and others (1987a) compiled the locations of 1538 earthquakes within a 19-mile-wide (30 km) zone along the surface trace of the WFZ for the period July, 1962 through December 31, 1986. The largest event had a magnitude of 5.2. Careful evaluation of those earthquakes with well-located foci showed that the hypocenters do not fall on the WFZ, if the WFZ is assumed to dip at an angle of 45° to the west. Rather, the earthquakes appear to be associated with secondary structures of moderate to high dip angles (>30°). The corre-

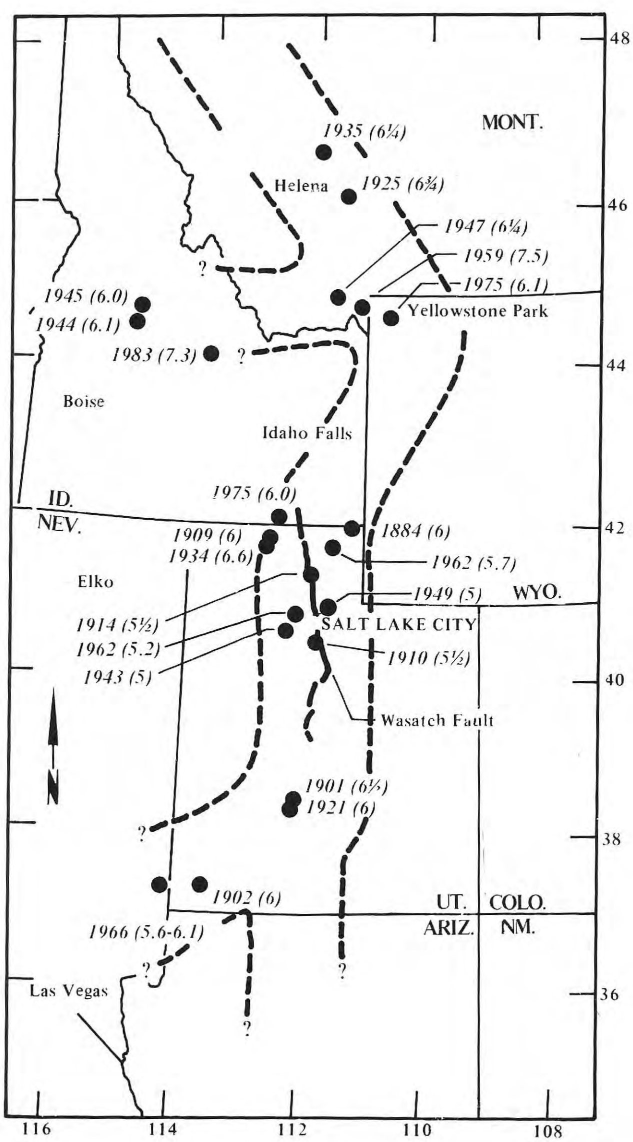



*Figure 14. The Intermountain seismic belt with the largest historic earthquakes indicated by dots (modified from Arabasz and Smith, 1981).*

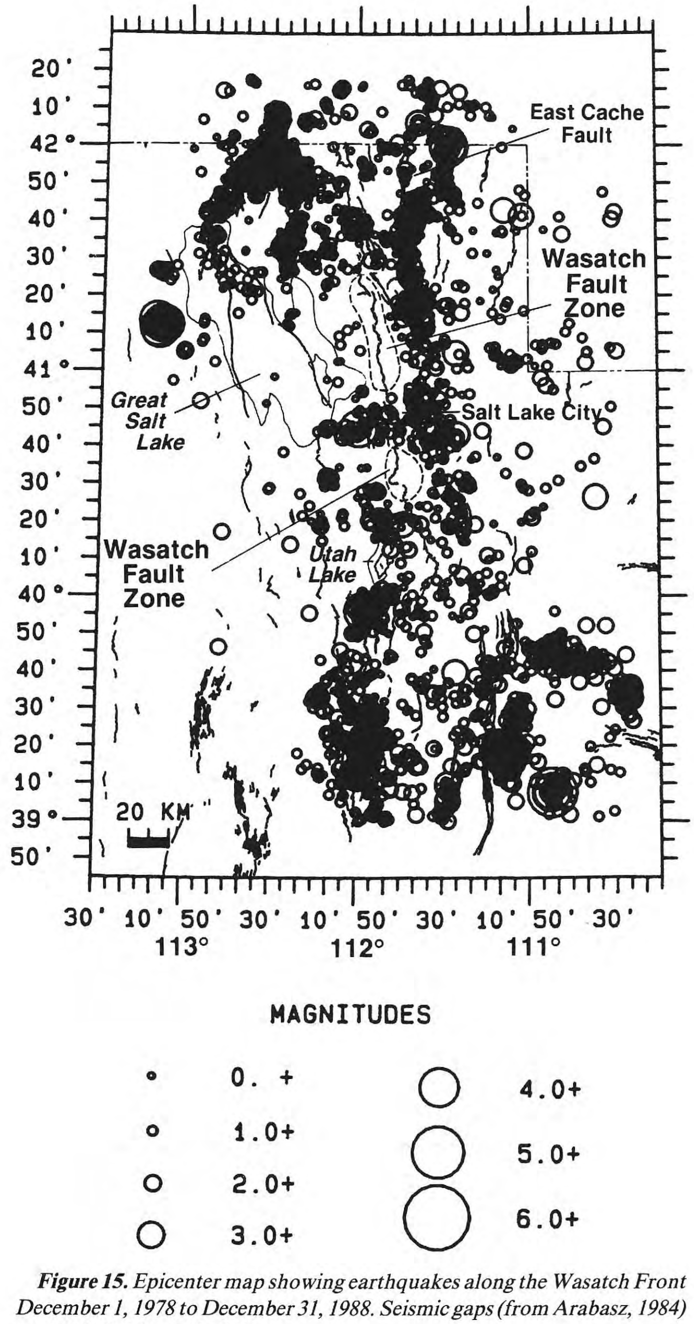



*Figure 15. Epicenter map showing earthquakes along the Wasatch Front December 1, 1978 to December 31, 1988. Seismic gaps (from Arabasz, 1984) are encircled by dashed lines.*

lation between large surface-faulting earthquakes on the WFZ and these numerous smaller events is unclear. However, geologic evidence for repeated Holocene surface faulting along the WFZ indicates that the absence of seismic activity on the fault zone has not persisted through geologic time.

Apparent seismicity gaps along the WFZ both north and south of Salt Lake City (figure 15) have been recognized (Arabasz and others, 1979c; Arabasz and Smith, 1981; Arabasz, 1984). They may, or may not (Arabasz and Smith, 1981), represent a low-activity stage in the seismic cycle of the fault zone. If they are related to the seismic cycle of the fault zone, the gaps may either represent: 1) a post-earthquake period following release of stress and decrease in aftershocks, or 2) a pre-earthquake period representing a high level of strain accumulation (Arabasz and others, 1979c; Arabasz and Smith, 1981). The gaps remain the subject of continuing study.

A second noteworthy feature regarding recent earthquakes in the Salt Lake City region is the pronounced clustering of seismicity east of the WFZ beneath the Wasatch Range from about Salt Lake City northward into Idaho (figure 15). The earthquake epicenters define a broad north-trending zone of intense, mostly microseismic, activity that cannot be correlated with known active faults. The high level of essentially continuous background seismicity indicates that occasional larger events may be expected (Arabasz and others, 1979c).

Earthquakes as large as $M_L$ 5.2 have been recorded along the east side of the Salt Lake Valley, but no evidence of either historical or prehistorical fault rupture has been found there. An epicentral clustering of small events is present at the north end of the WVFZ. The largest event had a magnitude of $M_L$ 4, but most of the earthquakes have been in the $M_L$ 2-3 range. The relationship between observed seismicity, the WVFZ, and the WFZ is not well understood.

## NOTABLE EARTHQUAKES

Although located within a pronounced zone of earthquake activity and astride a major, active fault zone, Salt Lake City has not been subjected to a large, destructive earthquake. Numerous felt events have occurred, but only a few have caused appreciable damage (Cook, 1972; Rogers and others, 1976; Oaks, 1987; Hopper, 1988).

The $M_S$ 6.6, 1934 Hansel Valley earthquake (figure 14) produced MM intensity VIII shaking in Salt Lake City and caused tall buildings to sway and "batter against" each other (Oaks, 1987). Kaliser (1971) reports that a clock mechanism weighing more than 2 tons (1.8 tonnes) fell from the main tower of the Salt Lake City County Building and "crashed through the building." The only death attributed to an earthquake in Utah occurred during the Hansel Valley event when the walls of a excavation collapsed on a public-works employee south of downtown Salt Lake City. There were numerous reports of broken windows, toppled chimneys, and structures twisted on their foundations.

Earthquakes in 1909, 1914, and 1943 (figure 14) produced MM intensities in Salt Lake City of up to VI, and earthquakes in 1910, 1949, and 1962 had MM intensities of VII in Salt Lake City (Oaks, 1987). Damage produced by these events included broken windows, cracked walls, fallen plaster, toppled chimneys, and buildings shifted on their foundations. The 1949 earthquake also ruptured a water main, resulting in loss of water to a portion of the city (Rogers and others, 1976).

An $M_L$ 5.7 earthquake with an epicentral MM intensity of VIII occurred in 1962 near Logan, Utah (figure 14). It is Utah's most destructive earthquake, causing an estimated $1 million damage in the epicentral area (Cook, 1972). The effects of the earthquake in Salt Lake City, where it was felt with a MM intensity of V or less, were minor.

Two earthquakes occurring outside of Utah have been strongly felt in Salt Lake City. The 1975 Pocatello Valley, Idaho earthquake (figure 14) had a $M_L$ of 6.0 and MM intensity of VIII in the epicentral area (Arabasz, and others, 1979a). In Salt Lake City, it had an MM intensity of IV and caused tall buildings to sway (Rogers and others, 1976). Other damage was slight. The most recent widely felt event was the 1983 Borah Peak, Idaho earthquake ($M_S$ 7.3), located about 250 miles (400 km) north of Salt Lake City (figure 14). Causing more than $12.5 million in damage over a broad region, its effect in Salt Lake City was minimal. Some taller buildings in the downtown area swayed and a typewriter reportedly fell from a desk.

## EARTHQUAKE RECURRENCE AND SLIP RATES

### Recurrence Models From Observational Seismic Data

Arabasz and others (1987a) evaluated earthquake recurrence rates for the Wasatch Front region using the record of 445 independent main events of $2.0 \leq M_L \leq 6.0$ that occurred between July 1962 and December 1985. Average recurrence intervals (N) for earthquakes of various magnitudes were determined (table 2) using the following recurrence relationship derived from these data:

$$N = (2.51)10\text{-}(0.71 \pm 0.09)(M_L - 3.0)$$

Arabasz and others (1980) estimate that the earthquake catalog for the Salt Lake City region is complete at the $M_L \geq 5.5$ level beginning in 1878. The observed average recurrence interval for historic earthquakes of $M_L \geq 5.5$ is 14 years, which corresponds with the lower boundary of the calculated interval shown in table 2. Because earthquakes of $M > 6.6$ have not occurred along the Wasatch Front in historical time, average return periods calculated for events larger than about $M_L 6$ (table 2) represent an extrapolation of existing observational seismic data (Arabasz and others, 1987a).

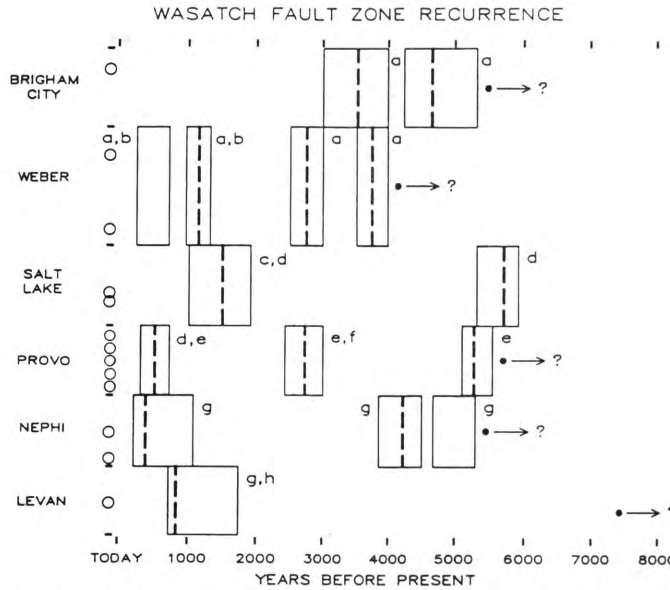
### Earthquake Recurrence and Slip Rates From Paleoseismic Data

**Wasatch fault zone** — Schwartz and Coppersmith (1984) used information derived from paleoseismic studies to calculate an average recurrence interval of 400 to 666 years for surface faulting anywhere on the WFZ since early Holocene time. Their preferred interval was 444 years. Where radiocarbon dates established the actual interval between events, recurrence was found to be non-uniform and to vary by as much as a factor of two.

**TABLE 2.**
*Average recurrence intervals calculated from observational seismic data for earthquakes in the Wasatch Front region[1] (Arabasz and others, 1987a).*

| | Average Recurrence Interval (years) | |
|---|---|---|
| $M_L$ | Preferred Estimate | Range of Estimates |
| ≥ 3.0 | 0.40 | |
| ≥ 3.5 | 0.90 | 0.81 - 1.0 |
| ≥ 4.0 | 2.0 | 1.7 - 2.5 |
| ≥ 4.5 | 4.6 | 3.4 - 6.3 |
| ≥ 5.0 | 10 | 7 - 16 |
| ≥ 5.5 | 24 | 14 - 40 |
| ≥ 6.0 | 54 | 29 -100 |
| ≥ 6.5 | 120 | 60 - 250 |
| ≥ 7.0 | 280 | 120 - 630 |
| 3.0 - 3.5 | 0.71 | .66 - .78 |
| 3.5 - 4.0 | 1.6 | 1.6 - 1.7 |
| 4.0 - 4.5 | 3.7 | 3.3 - 4.2 |
| 4.5 - 5.0 | 8.3 | 6.6 - 10 |
| 5.0 - 5.5 | 19 | 14 -26 |
| 5.5 - 6.0 | 42 | 28-66 |
| 6.0 - 6.5 | 96 | 57 - 170 |
| 6.5 - 7.0 | 220 | 120 - 420 |
| 7.0 - 7.5 | 490 | 240 - 1000 |

[1]38°55′N-42°30′N, 110°25′W-113°10′W, excluding mining-related seismicity in the southeast corner of the area.




Sources of data: a. Machette and others (1987), modified in this report; b. Swann and others (1980); c. Lund and Schwartz (1986); d. Schwartz and others (1988); e. Forman and others (1989); f. Schwartz and Lund (unpublished field data); g. Schwartz and Coppersmith (1984); h. Jackson (1988).

***Figure 16.*** *Timing of surface-faulting earthquakes on the Wasatch fault zone during the past 6000 years. Heavy dashed lines indicate the best estimate of times of faulting and boxes indicate likely limits of faulting as determined from radiocarbon dates and thermoluminescence age estimates (modified from Schwartz, 1989).*

Incorporation of new paleoseismic data obtained since 1984 results in an average recurrence interval for the past 6000 years (period of most reliable data) of 340 to 415 years for surface-faulting earthquakes (estimated $M_L$ 7.0-7.5) on the WFZ (Machette and others, 1989). The preferred interval (Machette and others, 1989) is the maximum value of 415 years, somewhat less than the 490 year return period calculated by Arabasz and others (1987a; table 2) for $M_L$ 7.0-7.5 earthquakes in the Wasatch Front region. Average recurrence intervals determined from paleoseismic evidence for individual fault segments comprising the WFZ are highly variable but commonly are much longer, often exceeding 2000 years or more (Swan and others, 1980; Lund and Schwartz, 1986; Machette and Lund, 1987; Nelson and others, 1987a; Personius and Gill, 1987; Jackson, 1988; Schwartz and others, 1988; Forman and others, 1989; Machette and others, 1989; figure 16).

**Salt Lake City segment —** Detailed paleoseismic investigations have been made at two locations on the Salt Lake City segment of the WFZ. Swan and others (1981) excavated trenches at the mouth of Little Cottonwood Canyon southeast of Salt Lake City (figure 3). Samples of detrital charcoal were collected from alluvium deposited in a graben formed during the oldest surface-faulting event recorded in the trenches. Radiocarbon analyses gave age dates of 9000 (+400; -600), 7800 (+400; -600), and 8600 (+500; -400) $^{14}C$ yr BP for the samples. The age dates provide a minimum limiting age for the oldest faulting event of 8000 to 9000 years. At least one other surface-faulting event occurred after deposition of the charcoal and before the region was settled (Hanson and Schwartz, 1982). An average recurrence interval of 4000 to 4600 years was calculated using these dates and the two events. However, there are two other splays of the main fault at the site for which no subsurface data were obtained. It is possible that surface-faulting events that occurred on those splays were not recorded on the fault that was trenched. Therefore, the 4000 to 4600 year recurrence interval is a maximum for the site (Hanson and Schwartz, 1982). The moraines at the mouths of Little Cottonwood and Bells Canyons adjacent to the trench site are offset vertically approximately 47.5 feet (14.5 m) by the WFZ (figure 11). Using an average displacement of 6.6 feet (2 m) per event, as determined from the trenching at the Little Cottonwood Canyon site, Swan and others (1981) calculated an average recurrence interval of 2400 to 3000 years for an estimated 7 to 8 events since deposition of the moraines 19,000 ± 2000 yr BP. They calculated a slip rate for the fault of 0.03 inches/year (0.76 mm/yr), but realized that the slip would be larger if the average displacement per event was larger than 6.6 feet (2 m).

The other trench site on the Salt Lake City segment is at Dry Creek, 1.5 miles (2.4 km) south of Little Cottonwood Canyon at the base of the Wasatch Range (figure 3). Trenches excavated in late Pleistocene to mid-Holocene deposits exposed evidence for two surface-faulting earthquakes (Lund and Schwartz, 1986). Calendar-calibrated radiocarbon dates from soil A horizons buried by scarp-derived colluvium constrain the age of both events. The most recent event took place shortly after 1600 to 1830 yr BP. The older event occurred shortly after 5455 to 5975 yr BP (Schwartz and others, 1988). The interval separating the two earthquakes is 3625 to 4375 years.

Net vertical tectonic displacement for the most recent event at Dry Creek, determined from offsets measured in trenches and from topographic profiles of fault scarps, is 14.8 to 15.6 feet (4.5-4.75 m), the largest displacement yet measured on the WFZ (Lund and Schwartz, 1986). The slip rate for the interval separating the most recent and penultimate events is 0.04 to 0.05 inches/year (1.0-1.3 mm/yr).

By combining observations from the Little Cottonwood Canyon and Dry Creek sites, it appears that there have been three large-magnitude, surface-faulting earthquakes on the Salt Lake City segment during the past 8000 to 9000 years. One event occurred shortly before 8000 to 9000 yr BP, one occurred shortly after 5500 to 6000 yr BP, and the most recent event occurred shortly after 1600 to 1830 yr BP. Taking into account the uncertainties in timing of events, intervals of 4000 ± 1000 years may best characterize the recurrence of large, surface-faulting earthquakes on this segment of the WFZ (Schwartz and Lund, 1988).

**West Valley and East Great Salt Lake fault zones —** The West Valley fault zone (WVFZ; figure 3) has evidence of at least six surface-faulting events within the past 13,000 years (Keaton and others, 1987a). The relationship between the WVFZ and the WFZ is unclear, and the exact timing of surface-faulting events on the WVFZ is unknown. Therefore, it is speculative whether surface-faulting events on the WVFZ were accompanied by earthquakes on the WFZ, or if they were generated by the WFZ with the WVFZ acting as an antithetic fault bounding a mega-graben (Keaton, 1989). The Granger fault (figure 3) has a slip rate of 0.018 to 0.021 inches/year (0.42-0.54 mm/yr) and a recurrence interval of 2700 to 3500 years for the past 12,000 years, and has a minimum slip rate of 0.003 inches/year (0.08 mm/yr) and a recurrence interval of 24,000 to 27,000 years for the past 138,000 years (Olig and others, 1986). The relationship between variations in the WVFZ's slip rate and the paleolakes that occupied the Salt Lake Valley is unclear, but it is apparent that the slip rate has not been constant (Keaton and others, 1987a). The Taylorsville fault is characterized by monoclinal warping down to the east rather than by offset across a discrete slip surface. It has a slip/flexure rate of 0.008 to 0.012 inches/year (0.21-0.30 mm/yr) and a recurrence interval of 5000 to 7000 years for the past 12,000 years (Olig and others, 1986).

Because the East Great Salt Lake fault zone is submerged beneath the Great Salt Lake (figure 3), information on the timing of past earthquakes is limited. However, Viveiros (1986) estimated slip rates for the fault of 0.038 inches/year (0.96 mm/yr) during the Pliocene and 0.058 inches/year (1.48 mm/yr) during the Quaternary based on sediment thickness in the associated subsiding basin and on fault geometry (Arabasz and others, 1987b). Pechmann and others (1987) arrived at a slip rate of 0.02 to 0.03 inches/year (0.4-0.7 mm/yr) by considering fault dip and sedimentation rates in the basin adjacent to the fault (Arabasz and others, 1987b).

# GEOTECHNICAL CHARACTERISTICS

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## MATERIAL TYPES

Geologic units that influence foundation design in the Salt Lake City metropolitan area include bedrock along the valley margins and unconsolidated deposits of alluvial, colluvial, and lacustrine origin in the valley. These units can be categorized as pre-Lake Bonneville, Lake Bonneville, or post-Lake Bonneville in age. Thicknesses of the unconsolidated deposits range from less than 3 feet (1 m) on mountain slopes to more than 2000 feet (600 m) beneath the Salt Lake Valley west of the Salt Lake salient.

Exposed pre-Lake Bonneville deposits consist almost exclusively of bedrock and moderate- to well-cemented coalescing alluvial fans at the base of the Oquirrh Mountains. Generally, these units provide adequate bearing strength for building construction and, aside from locally difficult excavation characteristics, have few adverse geological characteristics. However, two bedrock units do exhibit adverse properties and merit special consideration. The Oligocene Norwood Tuff crops out on the Salt Lake salient and contains layers of tuffaceous siltstone and mudstone that swell when wet and shrink when dry (Gordon and Owen 1977; Van Horn, 1981; Davis, 1983a). The steeply dipping Triassic Ankareh Formation crops out on the east side of Salt Lake City at the mouths of Red Butte and Parleys Canyons and south of Emigration Canyon (Davis, 1983a). The upper and Mahogany members of this formation have shale and mudstone beds that are soft and often highly fractured. A core sample from the Mahogany Member at the mouth of Red Butte Canyon ranged from 0 to 26 percent Rock Quality Designation (Gordon and Beck, 1985). Surface exposures of the upper and Mahogany members weather rapidly and have provided the source material for numerous debris flows during the period between 1983 and 1985 in Wasatch Range canyons. Although no occurrences have yet been reported, the shale and mudstone layers representing the upper and Mahogany members, and the soils derived from them, may be expansive.

Lake Bonneville deposits consist of shore, nearshore, and deep-water sediments present at the surface over most of the Salt Lake Valley below an elevation of about 5200 feet (1585 m; figure 3). Sand and gravel deposits of shore and nearshore facies, as well as glacial till at the mouths of Little Cottonwood and Bells Canyons (figure 3) have high bearing strengths (3000-6000 lbs/ft$^2$; 0.15-0.30 Mpa; Keaton, 1989). Deep-water sediments generally are compressible, have lower bearing strengths (1000-1500 lbs/ft$^2$; 0.05-0.07 Mpa; Keaton, 1989), and consist of thinly bedded fine sand, silt, and clay that contain minor amounts (usually $<$10 percent) of coarse sand and gravel. The lacustrine clays seldom exhibit significant shrink/swell tendencies.

Post-Lake Bonneville deposits in the Salt Lake Valley are mostly associated with the Jordan River and its tributaries. Flood-plain alluvium consists of sand, silt, clay, and local gravel deposits (Scott and Shroba, 1985) and is coarser near the mountain fronts. Flood-plain alluvium may provide good foundation conditions, but it is often subject to flooding and high ground water, and exhibits low bearing strength (500-1500 lbs/ft$^2$; 0.02-0.07 Mpa; Keaton, 1989) locally, particularly near the Great Salt Lake. Low-terrace alluvium along the Jordan River and the lower reaches of its tributaries is fine grained and can exhibit low bearing strength (500-1500 lbs/ft$^2$; 0.02-0.07 Mpa; Keaton, 1989) and moderate to high shrink/swell capacity. These same terraces closer to the mountain front are underlain by sand and gravel which have greater bearing strengths (3000-6000 lbs/ft$^2$; 0.15-0.30 Mpa; Keaton, 1989).

Fine- to medium-grained, clean sand horizons are common in the shallow subsurface in both Lake Bonneville and post-Lake Bonneville deposits over much of the central portion of the Salt Lake Valley. Where saturated, these horizons are potentially liquefiable under earthquake ground-shaking conditions (Anderson and others, 1986).

Alluvial fans of post-Lake Bonneville age consist of poorly sorted, cobbley gravel that is locally bouldery in a matrix of sand, silt, and clay. These fans have been deposited at the mouths of canyons in the Wasatch Range and Oquirrh Mountains and consist of numerous storm-generated, debris-flow and flood deposits. The materials comprising the fans may, due to their method of deposition, have low soil densities (80-85 lbs/ft$^3$; 12.6-13.4 kN/m$^3$; Keaton, 1989) and low soil moisture contents. Such soils exhibit adequate bearing strength for most structures when dry, but may consolidate and collapse when wetted (Klauk, 1986). Although not widespread in the Salt Lake Valley, such collapse-prone deposits are present locally as evidenced by damage to a wing of the University of Utah Hospital constructed on an alluvial-fan deposit. The structure settled when a water line beneath the building broke and saturated the foundation soils (Reaveley, 1987).

Materials encountered in and near the Great Salt Lake during drilling for the Southern Pacific Railroad causeway included mirabilite (salt), clay, oolites, calcareous algae, and brine shrimp fecal pellets (Newby, 1980). Laboratory tests indicated that these deposits have very low bearing strengths ($<$ 500 lbs/ft$^2$; 0.02 Mpa; Keaton, 1989). Soil borings made in the Great Salt Lake between the south shore and Antelope Island encountered silty sand changing to clay with sand lenses at depth (Rollins, Brown, and Gunnell, Inc. and Creamer and Noble Engineers, 1987). Consolidation tests showed that these materials are somewhat compressible.

## EXPLORATION AND LABORATORY TESTING

Site-investigation techniques used by consulting firms in the Salt Lake City metropolitan area include exploratory pits and trenches, borings, and geophysical exploration. Exploratory pits allow detailed examination of subsurface materials *in situ* and also permit the recovery of large, undisturbed and disturbed samples. Trenches provide long, continuous exposures of subsurface materials and thus allow examination of the lateral continuity of strata. Trenches are used to locate faults and to determine the width of associated zones of deformation. Borings are used to obtain samples below the ground-water surface and at greater depths than those achieved by exploratory pits or trenches. Borings in rock are commonly made using rotary-drilling methods, while continuous-flight augers are generally used for borings in soil. Augers may be hollow stem or solid flight; however, hollow stem is preferred because the design facilitates sampling. Soil samples are obtained using either split-spoon, California drive, or Shelby tube samplers. Core barrels are used to sample bedrock. Measurement of seismic veolocities in bore holes is the most widely used geophysical technique for site characterization studies in the Salt Lake City metropolitan area. The primary purpose of this technique is to determine the low-strain level moduli used to estimate earthquake site response characteristics.

Field and laboratory tests are performed in accordance with specifications established by the American Society for Testing and Materials. Commonly used field tests include various types of load tests, packer tests, percolation tests, and density tests. Common laboratory procedures include determination of soil density and moisture content, Atterberg limits, shrinkage limits, gradation analysis, swell/consolidation, unconfined compressive strength, direct shear, vane shear, triaxial shear, California Bearing Ratio, permeability, specific gravity, and water soluble sulfate content.

## TYPICAL FOUNDATION DESIGNS

Foundation designs used in the Salt Lake City metropolitan area include spread footings, continuous-wall footings, mat foundations, piers, and piles. The foundation system used depends on the size of the structure and the soil and ground-water conditions at the site. Generally, spread and continuous-wall footings are used for small- to moderate-size structures in areas with high bearing-capacity soils. These foundations have been used for similar structures in areas of low bearing-capacity soils after the soft soils below footing elevations have been removed and replaced with structural fill. Mat foundations are frequently used for moderate-size buildings where the soil has low bearing capacity. Piers and piles have been used for some moderate-size buildings in areas with low bearing-capacity soils and are also used for high-rise structures.

Liquefaction-susceptible soils are widespread in the Salt Lake Valley (Anderson and others, 1986; Gill, 1987) and are increasingly recognized as requiring special foundation treatment. At one building site in Salt Lake City, the vibratory pile method of soil densification was used to mitigate a liquefaction problem (Gordon, 1987).

To limit expected damage from earthquake ground shaking, base isolation foundation systems recently have been installed in two Salt Lake City buildings: the 103-year old City and County Building (table 3), and a new, computerized flight-simulator manufacturing facility. The base isolators consist of layers of thin rubber and steel bonded together as a single unit. They are stiff in a vertical direction and flexible in a horizontal direction allowing the building to "float" over the top of a fixed retaining wall system during a seismic event (Reaveley, 1989).

Major engineered structures representative of the types of foundations used in the Salt Lake City metropolitan area are shown in table 3.

Table 3. Major engineered structures in the Salt Lake City metropolitan area.

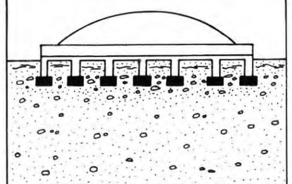
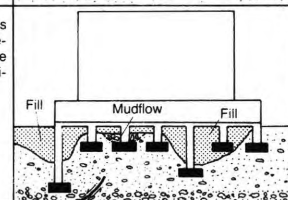
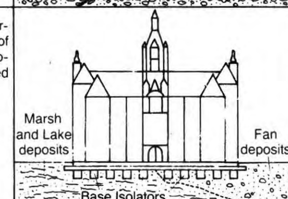
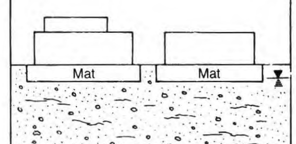
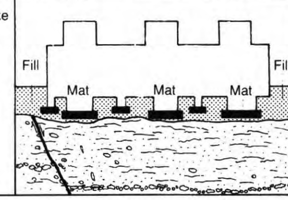
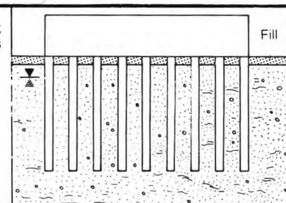
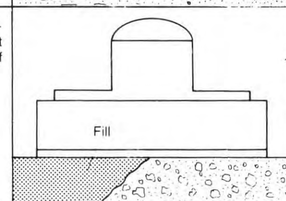
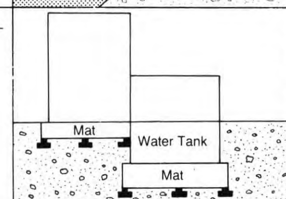
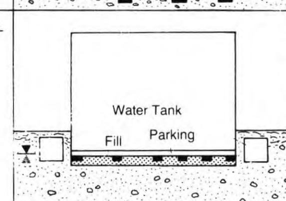
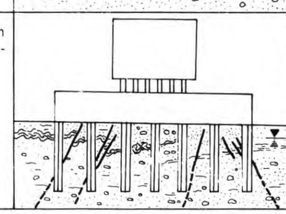
| Structure/ Address | Date of Construction | Foundation Type/ Seismic Resistant Structural System | Foundation Material | Subsurface Profile | Comments | References |
|---|---|---|---|---|---|---|
| John M. Huntsman Special Events Center, 1830 East and South Campus Drive, Salt Lake City, Utah. | 196 | Continuous wall footings and spot spread footings under columns. | Late Pleistocene and early Holocene fan alluvium. Map unit Qlb. |  | Liquefaction potential low; ground water 30-50 ft (9-15 m) deep; it was recommended that footings be placed in coarse gravel lens at 5 ft (1.5 m) beneath the surface due to soft silts and clays on site. | Joe Ruben, 1987, FFK&R Architects; Anderson and others, 1986; Scott and Shroba, 1985. |
| University of Utah Medical Center, 50 North Medical Drive, Salt Lake City, Utah. | 1964-1983 | Continuous wall footings and spot spread footings beneath columns, exterior envelope of reinforced concrete beams and columns with concrete walls between windows; interior beam and column system was designed and connected as a moment resisting structural frame. | Pre-Lake Bonneville alluvial-fan deposits (highly cemented); late Pleistocene "Bonneville" level gravel, sand and silt; Holocene mudflow and flash-flood deposits (collapsible sand and silt). Map unit Qb. |  | Liquefaction potential very low; ground water greater than 50 ft (15 m); old hospital building experienced settling problems in 1964, soil horizon responsible is in the mud-flow deposits; mudflow deposits were either removed and backfilled or spot spread foundations were placed below these deposits for the new structure; Pre-Lake Bonneville alluvium was faulted in the excavation, Lake Bonneville sediments were not displaced. | Lawrence Reavely, 1987, oral commun., Reavely Engineers and Associates; Dames and Moore, 1979; Scott and Shroba, 1985; Anderson and others, 1986. |
| Salt Lake City and County Building, Salt Lake City, Utah. | 1894 | Steel and concrete mat foundation; steel rails crisscrossed every 2 ft (0.6 m) and cement poured between them; continuous stepped footings; walls are load bearing brick, stone, and masonry construction; foundation retrofitted with base isolators to resist strong ground motion during seismic event. | Pleistocene and Holocene fan alluvium underlies north half of building; southern half of building underlain by Pleistocene and Holocene fine-grained alluvial-fan and mixed lake and marsh deposits. |  | Liquefaction potential moderate to high; ground water at 15 ft (5 m); evidence of differential settling (interior cracks) common throughout building; appears to have had a large settlement problem shortly after completion, but there are conflicting reports; 1934 Hansel Valley earthquake (Richter Magnitude 6.1) caused damage ranging from falling plaster to a crack in southeast corner of building; several more cracks formed due to earthquakes. | Kaliser, 1971; Anderson and others, 1986; Scott and Shroba, 1985. |
| Salt Lake County Government Center, 2001 South and State Street, Salt Lake City, Utah. | 1986 | Concrete mat foundation and 100 percent gravity steel frame with concrete shear walls; exterior brick walls anchored and braced. | Mixture of late Pleistocene Lake Bonneville sediments and Holocene alluvial-fan deposits. |  | Liquefiable deposits observed in borings in area from 10 to 20 ft (3-6 m); ground water at 12 ft (4 m); overexcavated and backfilled for mat foundation; foundation sealed and water proofed; no drainage system installed although foundation is below water table. | Lawrence Reavely, 1987, oral commun., Reavely Engineers and Associates; Anderson and others, 1985; Dames and Moore, 1980a; Van Horn, 1982. |
| American Express Building, 4315 South and 2700 West, Taylorsville, Utah. | 1983 | Continuous wall footings, large shear footings under towers, individual footings under columns; three concrete cores with large mat foundations to act against lateral shear. | Late Pleistocene and early Holocene Lake Bonneville silts and clays, Map unit Qlb. |  | Liquefaction potential moderate; ground water generally deeper than 10 ft (3 m); localized clay lenses divert irrigation water creating perched zones with water at 8 ft (2.4 m); evidence of liquefaction observed in trenches approximately 1100 ft (335 m) northeast of building; collapsible soils observed in foundation excavation; site overexcavated and backfilled; extension of Granger fault traverses the southwest corner of the site; several parallel faults found in trenches. | James Adkins, 1983, oral commun., KKBNA; Anderson and others; 1986; Dames and Moore, 1980a; Van Horn, 1982. |

Table 3 continued.

| Structure/ Address | Date of Construction | Foundation Type/ Seismic Resistant Structural System | Foundation Material | Subsurface Profile | Comments | References |
|---|---|---|---|---|---|---|
| McDonnell-Douglas Building, 1215 North and 2200 West, Salt Lake City, Utah. | 1987 | 12 in (30 cm) concrete-filled pipe piles driven to 90 ft (27 m); ductile concrete moment structural frame. | Holocene Jordan River flood-plain alluvium; primarily fine sand with pebbles and lenses of silt and clay. Map unit Qfpd. |   | Liquefaction potential high; ground water at or near surface, overexcavated and back-filled above water level; no pumping system; building water-proofed and all water piped from foundation; soils have low bearing strength to 60-70 ft (18-21 m); dark gray organic clay at 25 ft (8 m) contains methane gas, combustible if over 5 percent. | James Adkins, 1983, oral commun., KKBNA; Anderson and others, 1986; Van Horn, 1982. |
| Utah State Capitol, Salt Lake City, Utah. | 1914 | Continuous wall footings and gravity frame structure with masonry infill walls. | Gravel and sand of late Pleistocene, trans-gressive Bonneville shoreline under east side of building and fill beneath west side of building. Map unit Qpsf. |   | Liquefaction potential low; ground water at 30-50 ft (9-15 m); building has experienced settling due to bridging of the sand infill; attached exterior skin provides little resistance to seismic forces, structure is vulnerable to moderate or larger earthquakes; splay of Warm Springs fault trends approximately 1000 ft (305 m) to the west. | Richard Tholen, 1983, oral commun., Managing Architect — State of Utah; Anderson and others, 1986; Scott and Shroba, 1985; Lawrence Reavely, 1987, oral commun., Reavely Engineers and Associates. |
| Eaglegate Plaza Office Tower, South Temple and State Street, Salt Lake City, Utah. | 1986 | Concrete mat foundation; spot spread footings beneath columns; 22-story high-rise tower has moment-resisting steel frame; 5-story low-rise has concrete shear wall structural frame; structures are separated by a seismic separation extension joint. | Upper Pleistocene, lower Holocene alluvial-fan deposits. Map unit Qa. |   | Liquefaction potential moderate; ground water greater than 40 ft (12 m); mat foundation beneath low-rise building is much lower than foundation for high-rise due to 40 ft (12 m) excavation for a 1 million gallon (3,785,000 l) water tank; splay of Warm Springs fault trends approximately 1100 ft (335 m) to the west. | Lawrence Reavely, 1987, oral commun., Reavely Engineers and Associates; Anderson and others, 1986; Scott and Shroba, 1985. |
| Heber M. Wells Building, 300 South and 200 East, Salt Lake City, Utah. | 1982 | Continuous wall footings with spot spread footings beneath columns on compacted fill; steel moment-resisting structural frame. | Upper Pleistocene, lower Holocene alluvial-fan deposits. Map unit Qa. |   | Liquefaction potential moderate to high; ground water at 12.5 ft (4 m); strong gasoline odor associated with water, possible leakage from a buried tank; deformed bedding observed in excavation, overexcavation removed material; indication of a pre-historic lateral-spread covering several square blocks in downtown Salt Lake City; subsurface drains and continuous pumping into buried holding tanks required. | Lynn Jones, 1983, oral commun., MHT Architects; Morris Page, 1987, oral commun., M.F. Page and Associates; Dames and Moore, 1980b; Anderson and others, 1986; Scott and Shroba, 1985. |
| Metropolitan Hall of Justice, 100 South and 200 East, Salt Lake City, Utah. | 1965 | Driven steel H-beam pile foundations; 50 ft (15 m) building on long single-story columns. | Disturbed Holocene fine-grained alluvial-fan and late Pleistocene lake and marsh deposits. Map unit Qlb. |  | Liquefaction potential moderate to high; ground water from 9-18 ft (3-6 m); drainage system with pumps in use constantly; numerous faults and deformed beds observed in excavation, probably caused by pre-historic lateral spread landslide in area; upper structure is extremely vulnerable to earthquake-induced ground shaking; one person injured from falling typewriter due to shaking from 1983 Borah Peak earthquake. | Lawrence Reavely, 1987, oral commun., Reavely Engineers and Associates; James Bailey, 1987, oral commun., E.W. Allen and Associates; Anderson and others, 1986; Scott and Shroba, 1985. |

## GEOLOGIC HAZARDS AND CONSTRAINTS

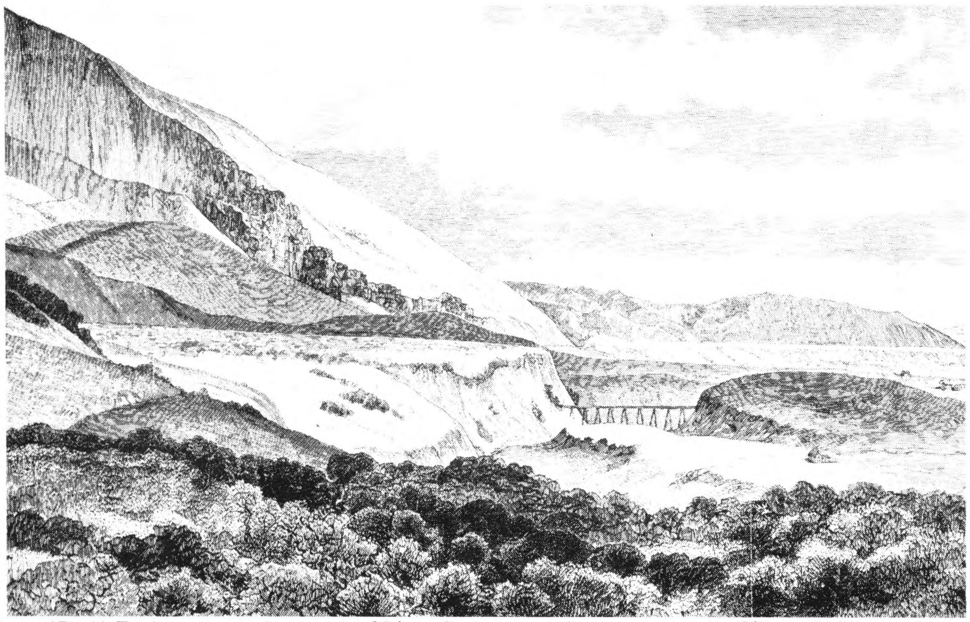
*Craig V. Nelson and William R. Lund*

Numerous geologic hazards exist in the Salt Lake City metropolitan area which can constrain land use. Active fault zones pose the threat of earthquakes, while steep mountains adjacent to the city create a potential for landslides, debris flows, rock falls, and snow avalanches. Streams and the fluctuating level of the Great Salt Lake create serious flood and ground-water problems. Considered as a whole, geologic hazards in the Salt Lake City metropolitan area confront planners with a variety of safety and economic issues that must be addressed before wise development can take place.

### EARTHQUAKE HAZARDS

The hazard presented by earthquakes to Salt Lake City has long been recognized. This warning by G.K. Gilbert (1883), of the U.S. Geological Survey, appeared more than 100 years ago in the *Salt Lake Daily Tribune:*

> *"It is useless to ask when this disaster (an earthquake) will occur. Our occupation of the country has been too brief for us to learn how fast the Wasatch grows; and indeed, it is only by such disasters that we can learn. By the time experience has taught us this, Salt Lake City will have been shaken down."*



A

***Figure 17.*** *A) Fault scarps at the mouth of Little Cottonwood Canyon as seen by Gilbert (1890), and B) as they appear today. Note condominiums in B constructed within the graben formed by the main and antithetic faults (Photograph credit, G.E. Christenson).*

B

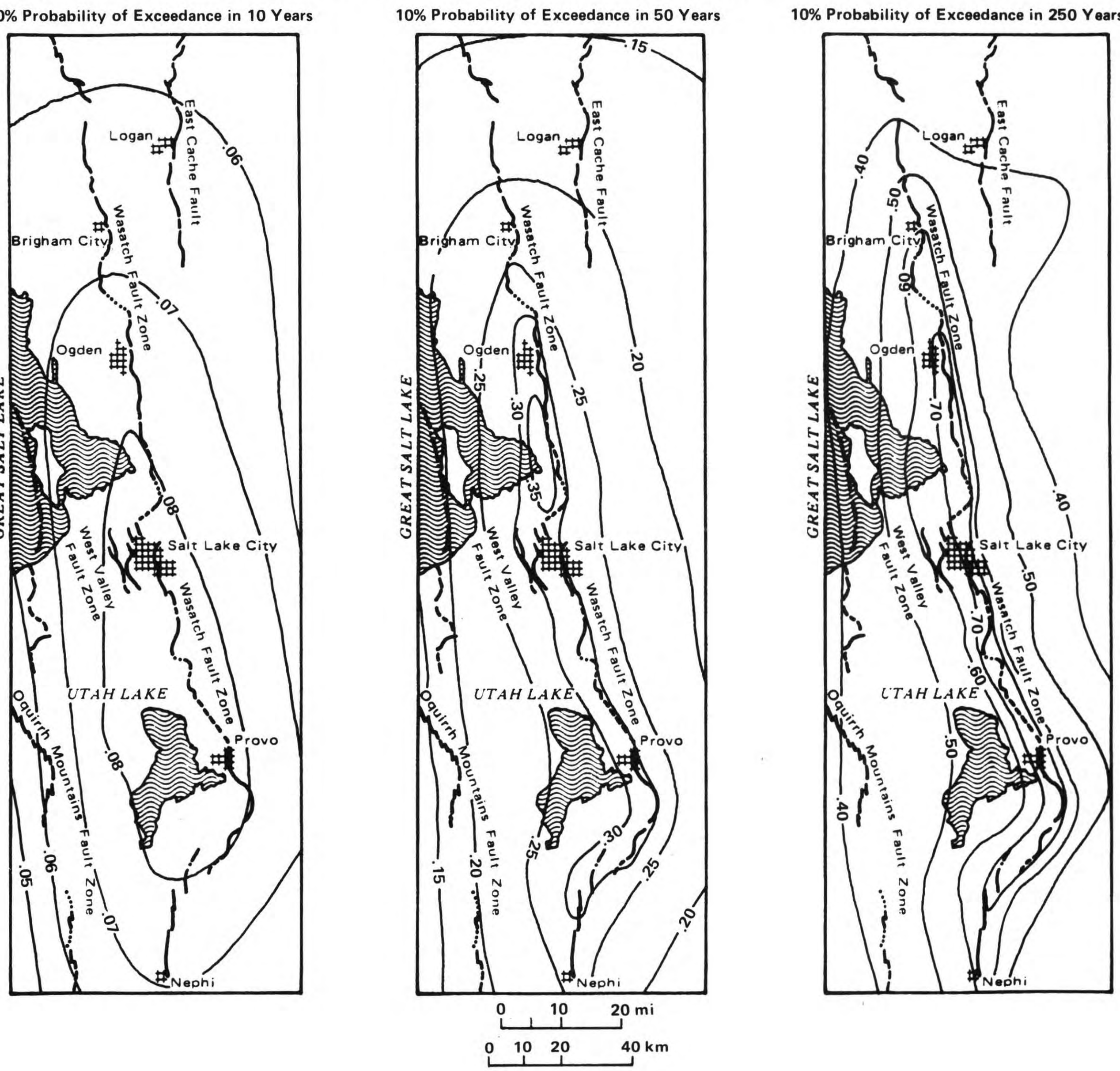
Gilbert recognized the extent of surface-fault deformation in the Salt Lake City area (figure 17) and its possible consequences. Earthquake hazards likely to affect Salt Lake City include ground shaking, ground rupture, tectonic deformation, liquefaction, seismically induced slope failures, seiche waves on the Great Salt Lake, and phenomena related to ground-water effects.
Salt Lake Valley (Hays, 1987). Algermissen and others (1988) estimated that ground-shaking damage from a $M_S7.5$ earthquake on the Salt Lake City segment would exceed $5.5 billion.

Examples provided by historic, large, normal-faulting earthquakes in the ISB (Hebgen Lake and Borah Peak) indicate that strong ground motion will accompany a similarly large earthquake

## Ground Shaking

Salt Lake City is susceptible to ground shaking from both nearby and distant earthquakes. The west-dipping geometry of the WFZ will place the hypocenter of earthquakes on the Salt Lake City segment of the WFZ directly beneath the heavily urbanized on the WFZ. National probabilistic seismic-risk maps prepared by Algermissen and others (1982) show that, for a 50-year exposure time, peak horizontal ground acceleration at rock sites in the Salt Lake City metropolitan area have a 10 percent probability of exceeding 0.28 g. This is higher than the 0.21 g previously calculated due to an increased appreciation of Holocene surface faulting

*Figure 18. Contours of peak ground acceleration on soil sites with 10 percent probability of being exceeded in 10 years, 50 years, and 250 years. Peak accelerations on rock sites are expected to be approximately 10 percent higher than the values shown on the map for 10 percent probability of exceedance in 10 years and 20 percent higher than the values shown on the maps for 50 and 250 years (from Youngs and others, 1987).*



on the WFZ (Algermissen and Steinbrugge, 1984). Youngs and others (1987) prepared maps for soil sites in the Salt Lake City area showing peak ground accelerations with a 10 percent probability of exceedance in 10, 50, and 250 years (figure 18). The 50-year map shows the peak ground acceleration for soil sites in the Salt Lake City metropolitan area to be 0.35 g, well above earlier predicted values.

Much of Salt Lake City lies on unconsolidated, lake-bottom and basin-fill sediments which may amplify ground shaking to levels greater than that expected for bedrock (Hays and others, 1978; Hays and King, 1982, 1984; Hays, 1987). Hays and King (1982) prepared a ground-shaking hazard map for the Salt Lake City metropolitan area using ground motion generated by nuclear explosions at the Nevada Test Site. The ground motion was recorded using portable broadband seismigraphs at forty locations in the Salt Lake Valley. The recording sites included a wide variety of material types and physical properties in both unconsolidated deposits and bedrock. The map shows the spatial variation of site-amplification factors for the period band 0.2 to 0.7 seconds relative to rock sites in the Salt Lake City metropolitan area (figure 19). This period band corresponds to the fundamental mode of response for buildings 1 to 7 stories high. The range of relative ground-shaking amplification varies from about two for sites underlain by thin, semi-saturated deposits of sand and gravel to as much as 10 for thick deposits of soft, saturated silt and clay. The level of site amplification increases toward the center of the Salt Lake Valley away from the WFZ. If subjected to ground-shaking amplifications of these magnitudes, many structures in the Salt Lake City metropolitan area would experience severe damage or collapse (Hays, 1987). Benz and Smith (1988) modeled the two-dimensional seismic response of the Salt Lake Valley to near- and far-field, normal-faulting earthquakes on the WFZ. Their analysis showed that near-field (within 30 miles; 45 km) directivity effects may be an important aspect of ground motion in the Salt Lake City area and should be given consideration in earthquake hazard assessments along the Wasatch Front.

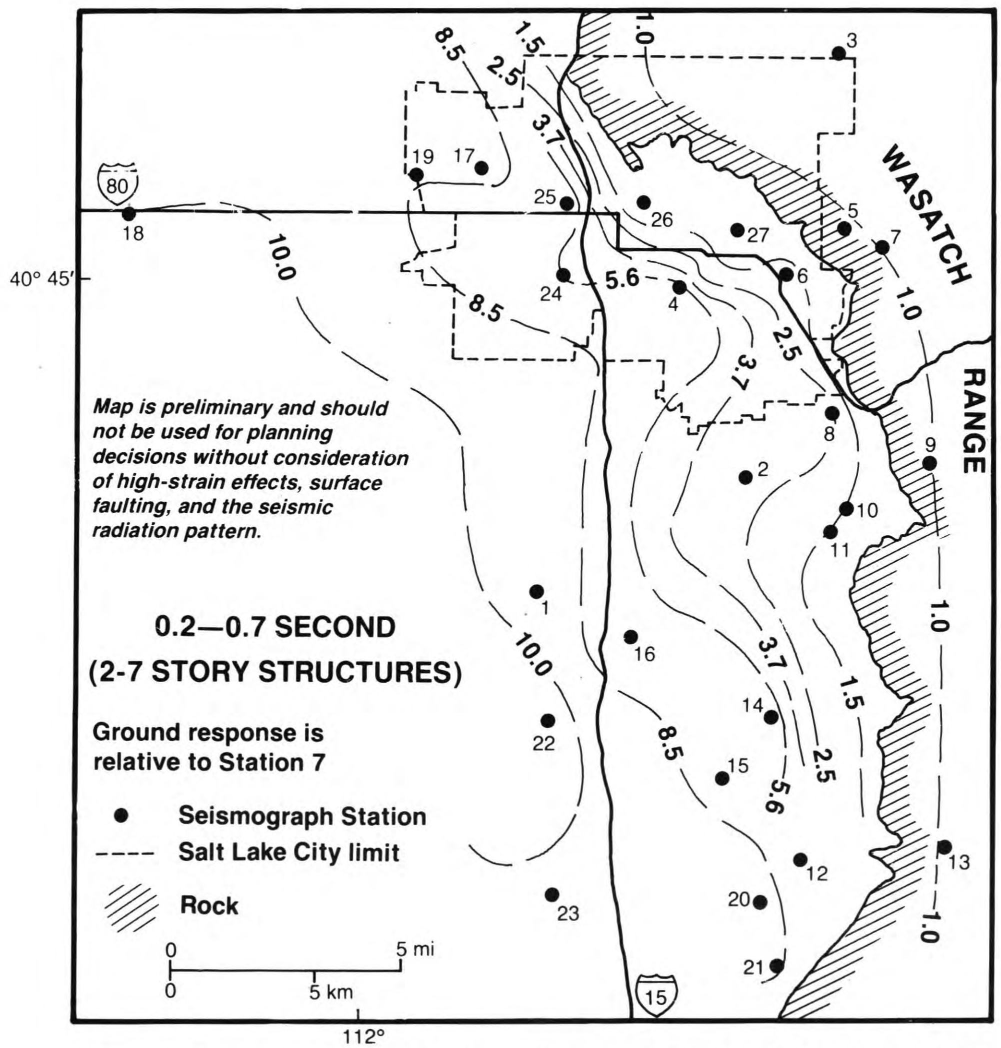



*Figure 19. Spatial variaiton of site-amplification factors for the period band 0.2 to 0.7 seconds for the Salt Lake City metropolitan area. Values on contours indicate the ratios of velocity response spectra that would be expected at sites underlain by soil relative to that experienced at sites underlain by rock on the Wasatch Front (from Hays and King, 1982; Hays, 1987).*

Rogers and others (1984b) expanded on the work of Hays and King (1982) by producing a map (figure 20) that correlates estimated horizontal ground-shaking response with unconsolidated deposits in the Salt Lake City metropolitan area. Unit descriptions were obtained from geologic maps and categorized into three broad groups: silt and clay, sand and gravel, and rubble (fill material). Figure 20 shows that for the short-period band (0.2-0.7 seconds), areas of the Salt Lake Valley underlain by silt and clay may experience ground shaking roughly six times stronger than bedrock locations; areas underlain by sand and gravel may experience ground shaking approximately four times greater than bedrock; and areas underlain by rubble (fill) should respond about three times greater than bedrock sites. Rogers and others (1984a) showed that, unlike the short-period band, mean-spectral levels for longer period bands are strongly influenced by the structure (geometry) of deeper, basin-fill deposits. Data available on the three-dimensional characteristics of the unconsolidated deposits in the Salt Lake Valley were not adequate for Rogers and others (1984b) to identify significant differences within the long-period band for the material categories used in their study.

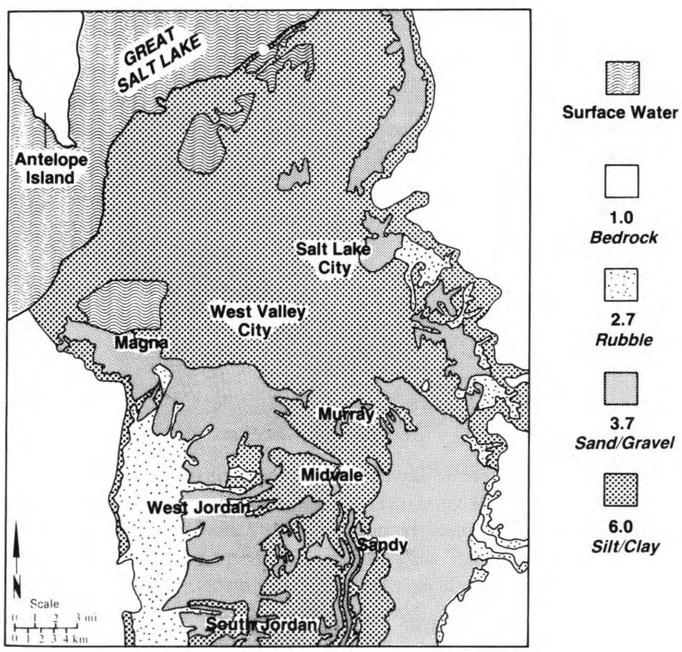



***Figure 20.*** *Estimated horizontal ground-shaking response for the period band 0.2 to 0.7 seconds for unconsolidated deposits relative to bedrock during an earthquake in the vicinity of Salt Lake City (from Rogers and others, 1984b).*

Borcherdt and others (1975) related horizontal ground velocity spectra to MM intensity in the San Francisco Bay area and found that a factor of two in mean spectral level represents a change of one MM intensity unit. Therefore, for short-period band rubble (fill) sites, MM intensities should be one to two units higher than MM intensities for an average rock site; sand and gravel sites are expected to experience intensities approximately two units higher than that for rock; and silt and clay sites should develop intensities two to three units higher than an average rock site (Rogers and others, 1984b).

## Ground Rupture

The areas of greatest ground-rupture hazard in the Salt Lake Valley are along the WFZ and WVFZ (figure 3). Neither fault zone has ruptured historically, but both show evidence of repeated movement during late Quaternary time. Their surface expression is seldom confined to a single trace, and most often consists of branching scarps that form broad zones of deformation up to 1000 feet (305 m) wide. Surface deformation can take the form of a single displacement, multiple step displacements, antithetic faults with associated graben, monoclinal flexures, backtilting, or complex combinations of these features. Net vertical tectonic displacements of more than 15 feet (4.5 m) per event have been measured on the WFZ (Lund and Schwartz, 1986), and single-event scarp heights (buried free faces) of 16 to 20 feet (5 to 6 m) which include the effects of back-tilting and graben formation, have been observed in trenches excavated across the WFZ (Lund, 1988). Olig and others (1986) determined an average deformation (slip/flexure) of 4.9 feet (1.5 m) per event for the WVFZ.

Numerous public and private facilities and many critical lifelines are built within or across the WFZ and WVFZ fault zones and would be damaged by a surface-faulting earthquake. The Salt Lake aqueduct, which supplies most of the culinary water used in Salt Lake City, crosses the WFZ more than 20 times (Kaliser, 1967). Large irrigation canals; buried utilities; railroads; Interstate Highway 80; and several large-diameter, high-pressure, petroleum pipelines cross the WFZ.

## Tectonic Deformation

It has been suggested from models of the 1959 Hebgen Lake and 1983 Borah Peak earthquakes, that large-scale tectonic subsidence may accompany surface-faulting earthquakes in the Salt Lake City region (Smith and Richins, 1984; Keaton, 1987). The magnitude and extent of this deformation can be estimated in three ways: 1) comparison with historical earthquakes in similar geologic settings, 2) theoretical computations, and 3) geologic studies to determine past deformation. Smith and Richins (1984) noted that during the $M_S$ 7.5 Hebgen Lake, Montana earthquake of 1959, up to 20 feet (6 m) of vertical displacement occurred over an area 11 miles (18 km) wide and 19 miles (31 km) long. They pointed out that if this amount of deformation resulted from movement along either the Salt Lake City or Ogden segments of the WFZ when the Great Salt Lake was at a high level, large areas in northern Salt Lake Valley would be inundated. The deformation associated with the Hebgen Lake earthquake is the largest associated with any historic earthquake in the ISB and can be considered a reasonable "worst case" scenario. Keaton (1987) recognized that the 19 feet (5.8 m) of vertical tectonic displacement in the 1959 Hebgen Lake earthquake was considerably larger than the 6.6 feet (2 m) of vertical displacement anticipated to accompany a

WFZ earthquake. Therefore, he applied a theoretical model to predict the likely effects of regional tectonic deformation. He found that the amount of deformation would be smaller than that which occurred at Hebgen Lake, but the effects still would be damaging. An evaluation of the tectonic deformation that may accompany an event producing 15 feet (4.5 m) of net vertical tectonic displacement (maximum measured on the WFZ to date; Lund and Schwartz, 1986) has not been made. Neither has the geologic record in the Salt Lake City region been systematically examined for evidence of regional tectonic deformation from prehistoric earthquakes. However, a progressive eastward shift in the position of the Great Salt Lake during Holocene time (Keaton, 1987) may be the result of tectonic deformation associated with the WFZ.

### Liquefaction

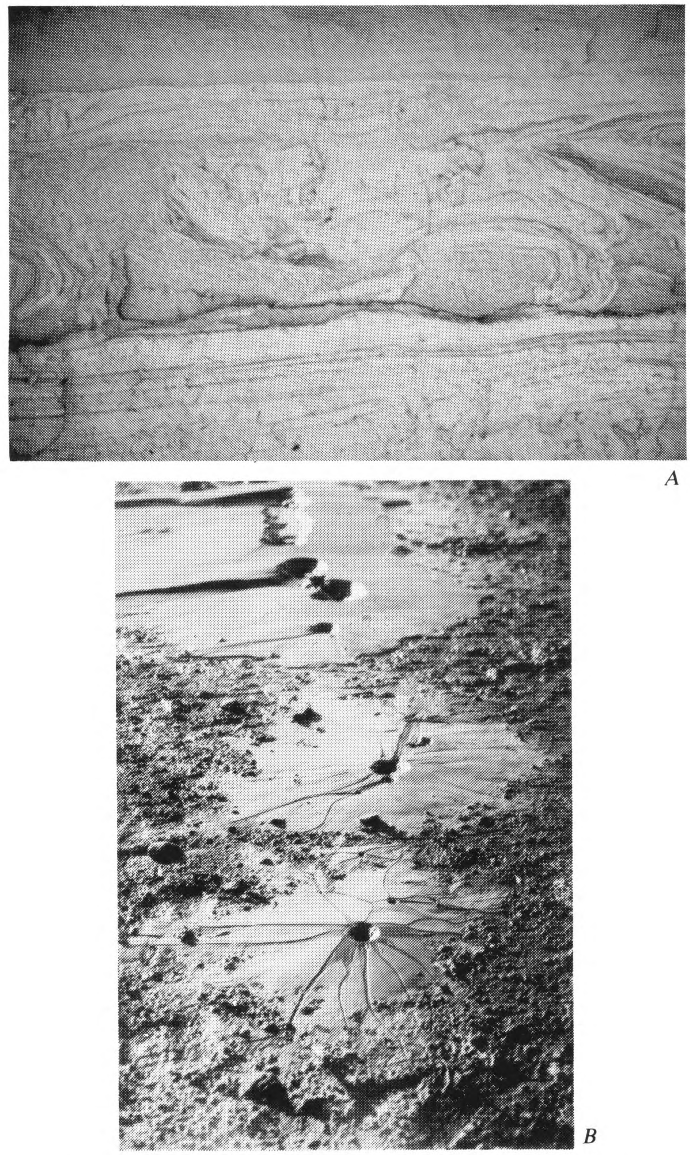
Fine-grained, saturated, lake-bottom sediments are common in the Salt Lake Valley and are susceptible to liquefaction-induced ground failure, including lateral-spread landslides and flow slides (Anderson and others, 1986). The largest lateral-spread landslide documented in the United States occurred in prehistoric time near Farmington 15 miles (24 km) north of Salt Lake City (Van Horn, 1973). Evidence for prehistoric liquefaction has also been observed in lake sediments exposed in excavations in the Salt Lake Valley (Gill, 1987; figure 21A). Liquefaction occurred historically in the mudflats near the Great Salt Lake during the 1934 $M_L$ 6.6 Hansel Valley earthquake (Walter, 1934; Robison, 1986; figure 21B).

Anderson and others (1986) have designated four classes of liquefaction potential in the Salt Lake City metropolitan area based on the probability that the critical acceleration required to induce liquefaction at a given site will be exceeded in 100 years. Ratings of very low, low, moderate, and high correspond to probabilities of less than 5 percent, 5 to 10 percent, 10 to 50 percent, and greater than 50 percent respectively. Much of Salt Lake City lies on soils having moderate to high liquefaction potential (figure 22).

### Other Earthquake-Related Hazards

Descriptions of twelve historic earthquakes in the Utah region between 1850 and 1986 include reports of seismically induced landslides or other kinds of ground failure (Keaton and others, 1987b). Failure types included rock falls, rock slides, soil slumps, lateral spreads and flows, and snow avalanches. Roads have been blocked, canals cut, and a water flume damaged. Future moderate-to-large earthquakes in the Salt Lake City region will undoubtedly be accompanied by slope failures and associated damage. Keaton and others (1987b) modeled seismic-slope stability in Salt Lake County and found moderate-to-high, earthquake-induced landslide potential over much of the mountainous portion of the county.

A major earthquake anywhere in northwestern Utah or a moderate earthquake in the immediate vicinity of the Great Salt Lake has the potential to generate destructive waves on the lake. Williams and Tapper (1953) reported that during the 1909 Hansel Valley earthquake (M 6.3) north of the Great Salt Lake: "At Saltair, waves rolled over the bathhouse pier and at Lucin cut-off, waves passed over the structure." Rogers and others (1976) describe these as "seiche" waves. At the time of the earthquake, the lake elevation was about 4206 feet (1282 m). More research is needed to assess the hazard from earthquake-generated waves on the Great Salt Lake.



A

B

*Figure 21. Evidence of liquefaction, both prehistoric (A) and historic (B). A) Sand dikes and contorted bedding associated with paleoliquefaction exposed in a foundation excavation in the Salt Lake City metropolitan area (photograph credit, H.E. Gill). B) Sand boils that formed as a result of the $M_S$ 6.6 1934 Hansel Valley earthquake in northern Utah (photograph credit, Special Collections, Marriott Library, University of Utah).*

The 1983 Borah Peak, Idaho earthquake ($M_S$ 7.3) produced numerous ground-water-related phenomena over a wide area. Ground water erupted from fissures and formed sand boils and craters in the epicentral area; ground-water levels rose over a wide area and some wells flowed briefly; flow increased in some springs and decreased or stopped in others; and numerous geysers, includ-

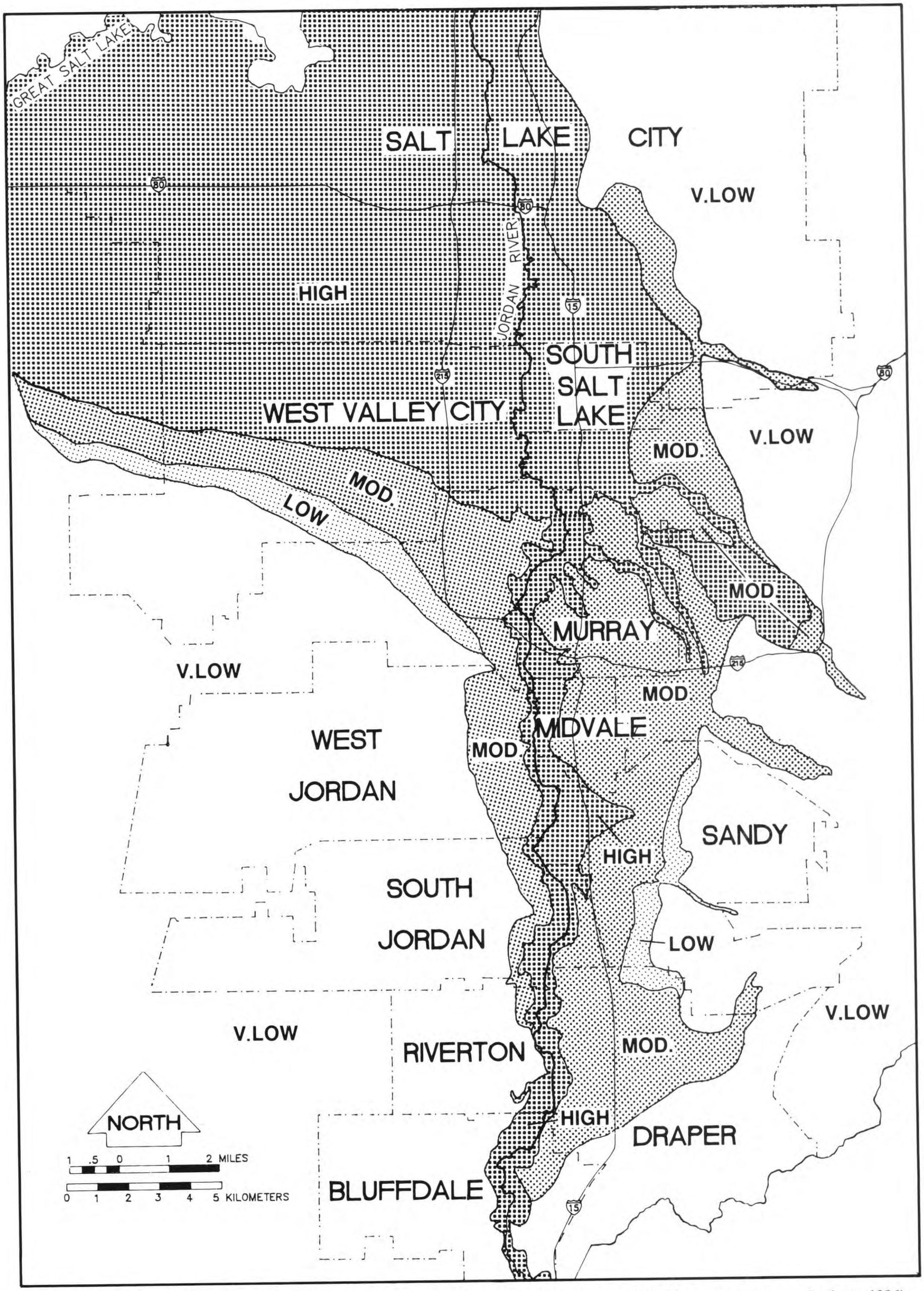



***Figure 22.*** *Liquefaction potential map for the Salt Lake City metropolitan area (modified from Anderson and others, 1986).*

ing Old Faithful, were affected in Yellowstone Park (Hutchinson, 1985; Waag, 1985; Whitehead, 1985; Wood, 1985). A large earthquake on the WFZ is expected to produce similar kinds of potentially damaging effects in the Salt Lake City metropolitan area.

## SLOPE STABILITY

Slope instability has not been a major problem in the Salt Lake City area, but as development moves higher into the foothills and nearby canyons slope stability is becoming a major issue affecting future development. Types of slope instability in the Salt Lake City area include rock fall, debris flow and debris flood, rotational and translational slumps, and earth flows. During unusually wet springs in 1983 and 1984 numerous slope failures in the Wasatch Range resulted in debris flows and floods that caused extensive damage to urban areas north of Salt Lake City (Anderson and others, 1984). Similar failures occurred in canyons adjacent to Salt Lake City, but none reached developed areas.

*Figure 23. Home destroyed by a slope failure in medium- to fine-grained Lake Bonneville deltaic sediments exposed in bluffs along Big Cottonwood Creek (photograph credit, W.R. Lund).*

Most unstable slopes are found in the canyons east of the city, along the steep flanks of Lake Bonneville deltas (figure 23), and in bluffs above incised streams. The geologic units most prone to slope failure are the Triassic Ankareh and Jurassic Preuss Formations in the canyons and fine-grained Lake Bonneville sediments in the valley. In Salt Lake County, 56 percent of all slope failures have occurred on hillsides where slopes range between 31 and 60 percent. That statistic prompted Salt Lake County in 1986 to lower the maximum allowable buildable slope from 40 percent to 30 percent. Even so, 23 percent of observed slope failures have occurred on slopes of 30 percent or less.

Range-front spurs susceptible to rock fall have been delimited by Case (1987); (figure 24). Although areas of rock-fall hazard are widespread, damage has been largely restricted to aqueducts and highways in canyon areas. Damage from this hazard will be extensive in the event of a moderate to large earthquake.

## AVALANCHE HAZARD

The Wasatch Range east of Salt Lake City receives an average annual snowfall of 33.8 feet (10.3 m) (Alder and Brough, 1985). Such heavy snowfall coupled with steep canyons create ideal conditions for avalanches. Utah's greatest avalanche disaster occurred in 1885 when the Little Cottonwood Canyon mining camp of Alta was leveled by a large avalanche and associated fire, killing 15 people (Perla, 1971). Perhaps as many as 250 persons perished in snow slides in the Big and Little Cottonwood mining districts during the 1865-1939 mining period (Bowman, 1967). Since then, avalanche fatalities have averaged less than 1 per year (Williams and Armstrong, 1984) and are suffered mainly by back-country skiers. This reduction in deaths is due in large measure to the research on avalanche hazards conducted from the early 1960s to 1972 by the U.S. Forest Service at the Alta Avalanche Study Center. Although research activities have since been moved to Fort Collins, Colorado, the U.S. Forest Service maintains an Avalanche Forecast Center in Salt Lake City that provides information on the avalanche hazard in the Wasatch Range during the winter months.

Because risk is generally confined to known avalanche paths in the Wasatch Range, Salt Lake County ordinances prohibit building permanent structures in known avalanche hazard areas (Salt Lake County, 1986). However, older structures built prior to adoption of the ordinances are still exposed to damage or destruction by avalanches (figure 25).

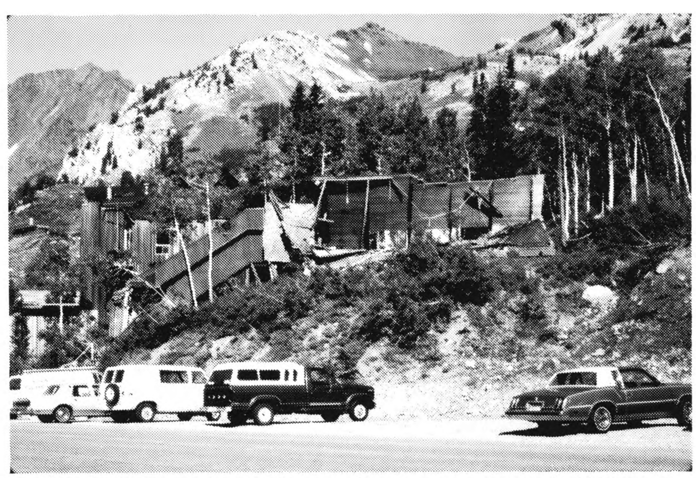


*Figure 25. Church in Alta destroyed by a snow avalanche in 1986 (photograph credit, W.R. Lund).*

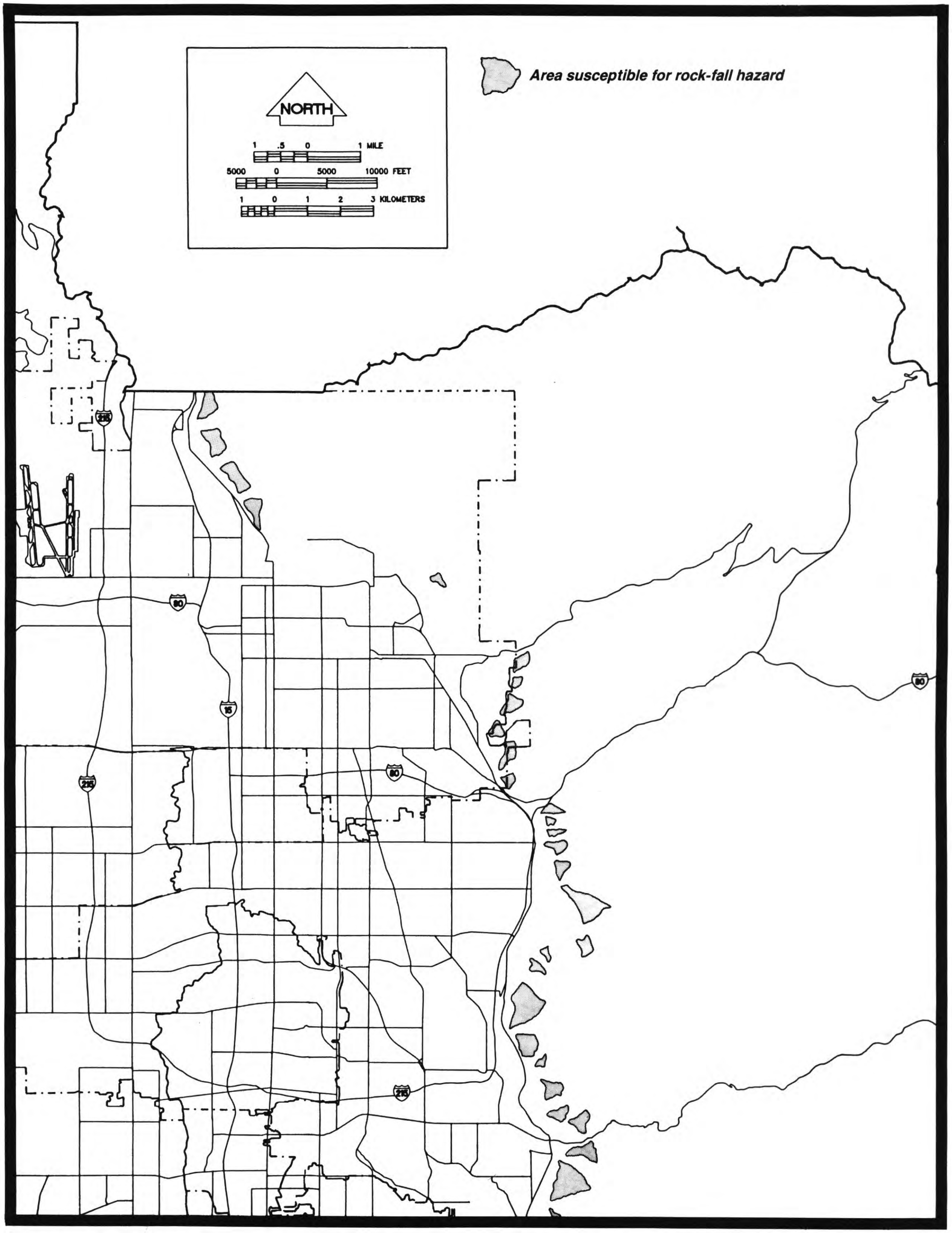



***Figure 24.*** *Rock-fall susceptibility in the Salt Lake City metropolitan area (from Case, 1987).*

## FLOOD HAZARD

Although located in a semi-arid region, Salt Lake City is subject to cloudburst and snowmelt floods. The Jordan River's three main northern tributaries are diverted into storm sewers beneath the city. During May and June 1983, a sudden warming trend rapidly melted a record mountain snow pack. The resulting runoff quickly exceeded the capacities of the storm sewers, and flood waters were then diverted onto city streets (figure 26). The flooding in 1983, and to a lesser extent in 1984, caused flood-control agencies to build sediment basins, install stream-bank protection, and dredge stream channels to reduce flood hazards. Flood plains along the Jordan River and its tributaries have been rated for expected flood heights by the Federal Emergency Management Agency (FEMA) and areas susceptible to 100-year flood-frequency inundation have been delimited on *FEMA Flood Boundary Maps.* These maps are updated as development occurs and channel obstructions, culvert modifications, and other changes alter potential flood heights and velocities. Salt Lake County ordinances require the lowest floor grades (including basements) in new construction to be a minimum of 1 foot (0.3 m) above the appropriate FEMA flood elevation.

***Figure 26.*** *Water diverted down State Street in Salt Lake City during the flood of 1983 (photograph credit, C.V. Nelson).*

Portions of Salt Lake City are also subject to flooding by the Great Salt Lake. Because it is a terminal lake with a nearly flat bottom, shoreline positions fluctuate considerably with changes in lake-level elevation. Increased precipitation during the first half of the 1980s caused a rise in the lake to its historic high of 4211.85 feet (1283.79 m) and resulted in $240 million in flood damage to public and private resources and facilities (Austin, 1988). It was necessary to raise Interstate Highway 80 and the Union Pacific Railroad at the south end of the lake. Evaporation ponds used by lakeshore mineral extraction industries were flooded as dikes were submerged and breached. The causeway to Antelope Island State Park was inundated, and public beach facilities and the headquarters building at Saltair Beach State Park were flooded. Saltair Pavilion, a private recreational park opened in 1983, was flooded and severely damaged by wave action (figure 27). Diking and pumping have been necessary to protect developed sections of northern Salt Lake City and stretches of the Jordan River. In June 1987, the State of Utah completed the $60-million West Desert Pumping Project designed to pump water from the Great Salt Lake to the West Desert and stabilize the lake level.

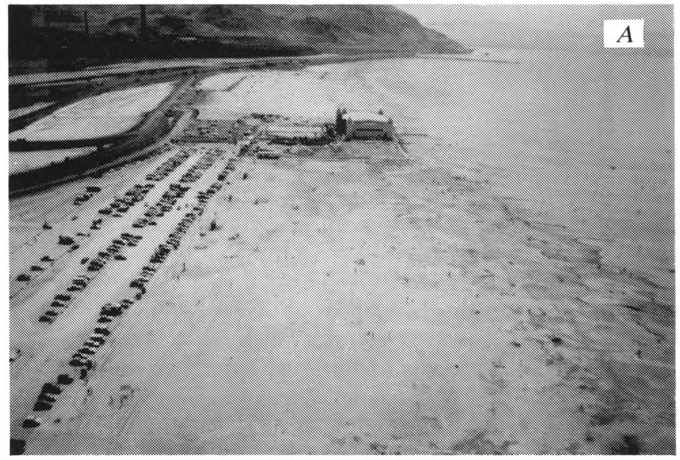



***Figure 27.*** *A) Saltair Pavilion on the south shore of the Great Salt Lake in July, 1983; B) Less than a year later in April, 1984 storm waves from the rising lake break against the structure (photograph credit, J. Silver).*


## SHALLOW GROUND WATER

Shallow ground water (0-10 ft; 0-3 m) poses a constraint to development in the central and northern sections of the Salt Lake Valley (figure 28). The Salt Lake Valley is part of a closed topographic basin, with the nearby Great Salt Lake receiving water from both streams and ground-water sources. Following three consecutive wet years from 1983 to 1985, many ground-water problems began to appear. An industrial complex near the Warm Springs fault was inundated due to increased spring flow, a central-valley motel swimming pool was damaged as increased ground-water buoyancy "lifted" the empty pool, and many homeowners suffered flooded basements. Local, shallow ground water and associated flooded basements have also resulted from leakage from unlined irrigation canals, flood-irrigation practices, and septic tank drain fields (Lund, 1981; Christenson, 1984). Other possible ground-water-related constraints include the need to protect aquifer recharge zones in foothill areas as they become urbanized, and the hazard associated with liquefaction of saturated soils during seismic events.

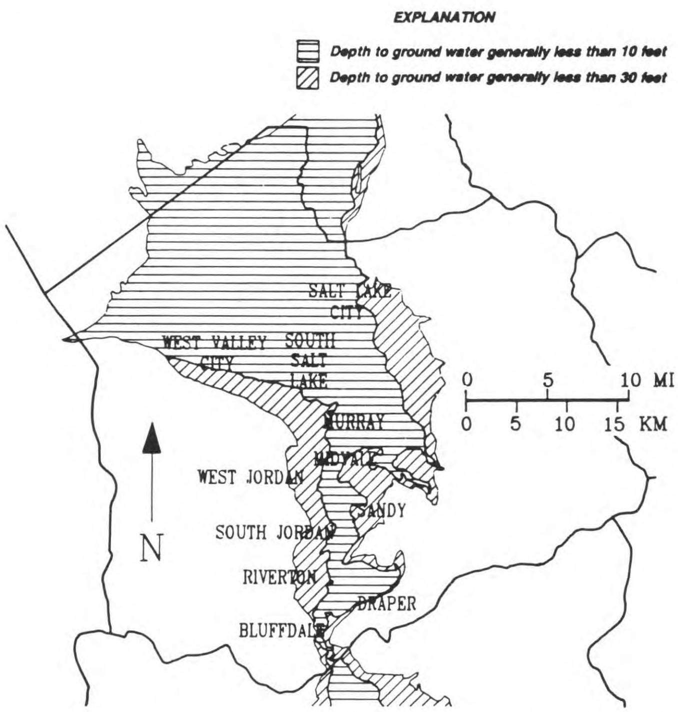



***Figure 28.*** *Areas of shallow ground water in the Salt Lake Valley (from Hecker and others, 1988).*

## GEOLOGIC HAZARD MITIGATION

Mitigation of geologic hazards and their associated risks in the Salt Lake City metropolitan area is based on a variety of ordinances adopted by several governmental entities. No single comprehensive hazard ordinance exists which is applicable to all parts of the metropolitan area. For that reason, both the level of mitigation required and the degree to which ordinances are enforced vary widely.

Salt Lake City and the other incorporated municipalities in the Salt Lake City metropolitan area, as well as Salt Lake County, have adopted the Uniform Building Code (UBC); (International Conference of Building Officials, 1988) as part of their building regulations. Section 2312 of the UBC "Earthquake Regulations" gives minimum specifications for earthquake-resistant design and construction. Based on anticipated levels of ground shaking, the Salt Lake City metropolitan area has been placed in Zone 3 of the UBC Seismic Risk Map of the United States (International Conference of Building Officials, 1988). Zone 3 indicates major damage corresponding to MM intensity VIII or higher. The Utah Seismic Safety Advisory Council (USSAC) was created in 1978 by the Utah State Legislature for a period of 4 years. In 1981, USSAC recommended more stringent construction requirements and established seismic Zone U-4 (Utah Seismic Safety Advisory Council, 1981). This zone incorporates the same seismic-design provisions as UBC Zone 3, but strengthens the review and inspection requirements to insure compliance. The Utah Legislature chose to let the USSAC charter lapse, and at present none of the agencies issuing building permits in the Salt Lake City metropolitan area have adopted the USSAC Zone U-4 recommendations.

In addition to the UBC, Salt Lake City, Salt Lake County, Sandy City, and Murray City have land-use zoning ordinances that address geologic hazards to a greater or lesser extent. Surface faulting is the only earthquake-related hazard that receives specific consideration in these ordinances. Salt Lake City's *Site Development Ordinance* (Salt Lake City, 1982) calls for a geologic report whenever a proposed development lies within 500 feet (152 m) of a known active fault. The report is to be prepared "by a firm or individual qualified by training and experience to have knowledge of the subject." The State of Utah does not register geologists or certify engineering geologists, but the ordinance defines an "engineering geologist" as "a graduate in geology or engineering geology from an accredited university, with five or more years of professional experience, at least three of which have been in the field of engineering geology." The report must contain an evaluation of geologic features "including but not limited to, stratification, stability, folds, zones of contortion or crushing, joints, fractures, shear zones, faults, and any other geological limitations." In addition, a written statement must be included identifying any geological constraints to development and stating the adequacy of the proposed development plan to mitigate or eliminate the problems so as to "prevent hazard to life, hazard to property, adverse affects on the safety, use, or stability of a public way or drainage channel, and adverse impact on the natural environment." A geologic grading report prepared by an engineering geologist may also be required at the completion of a project to verify that the intended use of the property is appropriate for the geologic conditions that exist there. Report reviews currently are performed by the Salt Lake County geologist. Both the pre- and post-development reports may, at the discretion of the City Planning Director, be submitted to the Utah Geological and Mineral Survey (UGMS) for additional review. Although many earthquake hazards are not addressed, Salt Lake City's *Site Development Ordinance* does state (Section 47-5-6.10) that "no structure shall be located over a fault" and that "the determination of an appropriate setback distance from the fault shall be made using the data compiled in the geologic report by the person or firm preparing the report." This provision was used in one instance to prevent construction of a multi-story apartment complex astride the East Bench fault (Nelson, 1988).

Salt Lake County's zoning ordinance (Salt Lake County, 1986) includes a *Hillside Protection Overlay Zone* (HPOZ) that applies to those areas of the county with slopes greater than 20 percent. The HPOZ allows the Planning Commission to require a geologic report if such a report is deemed necessary. The format for the report is taken directly from Salt Lake City's *Site Development Ordinance* (Salt Lake City, 1982). The ordinance requires the same evaluation of geologic features, including faults, and a written statement identifying the methods proposed to minimize the affects of geologic hazards. The reports are reviewed by the Salt Lake County geologist (Nelson and others, 1987b). The Planning Commission can withhold approval for any project determined to be in an area containing natural hazards until the applicant demonstrates that "identified hazards or limitations can be overcome in such a manner as to minimize hazard to life, limb, or property." In addition, the Planning Commission may set other requirements for the mitigation of natural hazards to insure that the purposes of the HPOZ are met. However, the effectiveness of the HPOZ is limited by its restricted geographic coverage. Much of the area included in the HPOZ lies above the Bonneville shoreline, generally upslope from the WFZ and many areas of shallow ground water and other geologic hazards. Consequently, considerable development has taken place in the county in areas of high risk from geologic hazards without adequate mitigation measures.

Fortunately, this situation has recently changed. The Salt Lake County Planning and Zoning Department adopted a *Natural Hazards Ordinance* (NHO) in 1989 (Salt Lake County, 1989). The new ordinance is more comprehensive in its geographic coverage than the HPOZ, and specifically addresses such earthquake-related hazards as surface-fault rupture and liquefaction. The boundaries of the NHO encompass the identified "special-study areas" of the county regardless of topography. Maps identifying natural-hazard, special-study areas are being prepared by the Salt Lake County Geologist. Development in a special-study area requires a report prepared by an experienced engineering geologist identifying "all known or suspected natural hazards, originating on site or off site that may affect the particular property." The report must also assess the hazards as they relate to the intended land use. Preliminary criteria have been developed by the Salt Lake County Planning Division for determining when site-specific reports are warranted (table 4). As adopted, the ordinance allows project approval to be withheld in any area containing significant natural hazards unless it can be demonstrated that the hazards can be mitigated effectively.

Sandy City's zoning ordinance contains a *Sensitive Area Overlay Regulation* (SAOR; Sandy City, 1989) applicable to areas with slopes greater than 10 percent. Among other things, the SAOR is intended to "minimize environmental hazards." A geologic-condition report is required for projects that fall within the area subject to regulation under the SAOR. The report must define "zones of deformation with respect to active faults and other masse movements of rock and soil." The ordinance prohibits construction of structures in zones of deformation associated with active faults. The SAOR incorporates the WFZ where it passes through Sandy. No other provisions are made in Sandy City ordinances for the identification or mitigation of geologic hazards.

Murray City's zoning ordinance states: "Whenever a geologic and soils survey report indicates a parcel to be subject to unusual potential or actual hazard, the applicant shall meet the special conditions required by the Planning Commission or Building Official, to reduce or eliminate such hazard, or if such condition cannot be met, or will not be met, the application shall be denied." The ordinance does not address earthquake hazards directly, nor does it establish guidelines for determining when a geologic report should be required.

Awareness of geologic hazards in the Salt Lake City metropolitan area is growing among planners, building officials, and others responsible for implementing public policy in Utah. However, much remains to be done to prepare for the many geologic hazards that may affect the area. Many municipalities do not include seismic-hazard mitigation measures in their building regulations or site development ordinances beyond those specified by UBC design standards. None have passed regulations for the retrofitting of existing buildings that do not meet current seismic-safety standards. For instance, Salt Lake City does not have a program to renovate or remove the large number of multi-story, unreinforced masonry buildings in the downtown area or to mitigate the hazard presented by poorly secured parapets and other building features susceptible to seismic damage.

**TABLE 4.**
*Matrix chart showing when natural hazard reports are required under Salt Lake County's Natural Hazards Ordinance.*

**NATURAL HAZARDS MAPS SPECIAL STUDY AREA REPORT REQUIREMENTS**
Is a Site Specific Natural Hazards Report Required Prior to Approval?

| Land Use (Type of Facility) | Liquefaction Potential HIGH & MODERATE | Special Study Area LOW & VERY LOW | Surface Fault Rupture Special Study Area | Avalanche Path Special Study Area |
|---|---|---|---|---|
| Critical Facilities (Essential and Hazardous Facilities, and Special Occupancy Structures; 1988 UBC Table No. 23-K) | YES | YES | YES | YES |
| Industrial & Commercial Buildings (> 2 stories or > 5 000 square feet) | YES | NO | YES | YES |
| Multi-Family Residential Structures (4 or more units per acre), and all Other Industrial and Commercial) | YES | NO | YES | YES |
| Residential Subdivision | YES | NO | YES | YES |
| Residential Single Lots and Multi-Family Developments (Less than 4 units/acre) | NO* | NO | NO* | YES |

**Although no special study is required, disclosure is required as described in Section 19.75.100*

# ENVIRONMENTAL CONCERNS

*Gary E. Christenson*

## WATER SUPPLY

Water is used in the Salt Lake City metropolitan area for municipal, domestic, fishery and recreation, and industrial purposes as well as for irrigation and stock watering. Water is obtained from a variety of sources, but principally from streams within the Jordan River and neighboring Colorado River drainage basins. Ground water from wells in the valley and springs in the Wasatch Range and Oquirrh Mountains is also utilized, but to a lesser extent. A summary of water use and sources is given in table 5. Sixteen different organizations are involved in supplying water to the Salt Lake City metropolitan area. The principal suppliers are the Salt Lake City Corporation, the Metropolitan Water District, and the Salt Lake County Water Conservancy District, but each municipality and many unincorporated areas have their own organizations which acquire and maintain water rights and construct storage and distribution facilities (Richins, 1987).

Municipal water comes from City, Parleys, Big Cottonwood, and Little Cottonwood Creeks; several smaller creeks farther south in the Wasatch Range; the Jordan River; and from Deer Creek Reservoir (figure 29). The water is treated in one of several water treatment plants in the Salt Lake Valley (Coon, King, and Knowlton Engineers, 1982; figure 29). Because most Wasatch Range canyons are part of the municipal watershed, both Salt Lake City and County have broad authority to control land use which may degrade water quality in those canyons. Ski resorts, private residences, businesses, and recreational activity in the canyons have created conflicts with watershed uses and locally have degraded water quality (Jensen and Lund, 1983). Salt Lake City recently completed a watershed management plan to protect the city's water rights (Bear West, 1987), and the Salt Lake County Public Works Planning Division has developed a canyon master plan to guide further development.

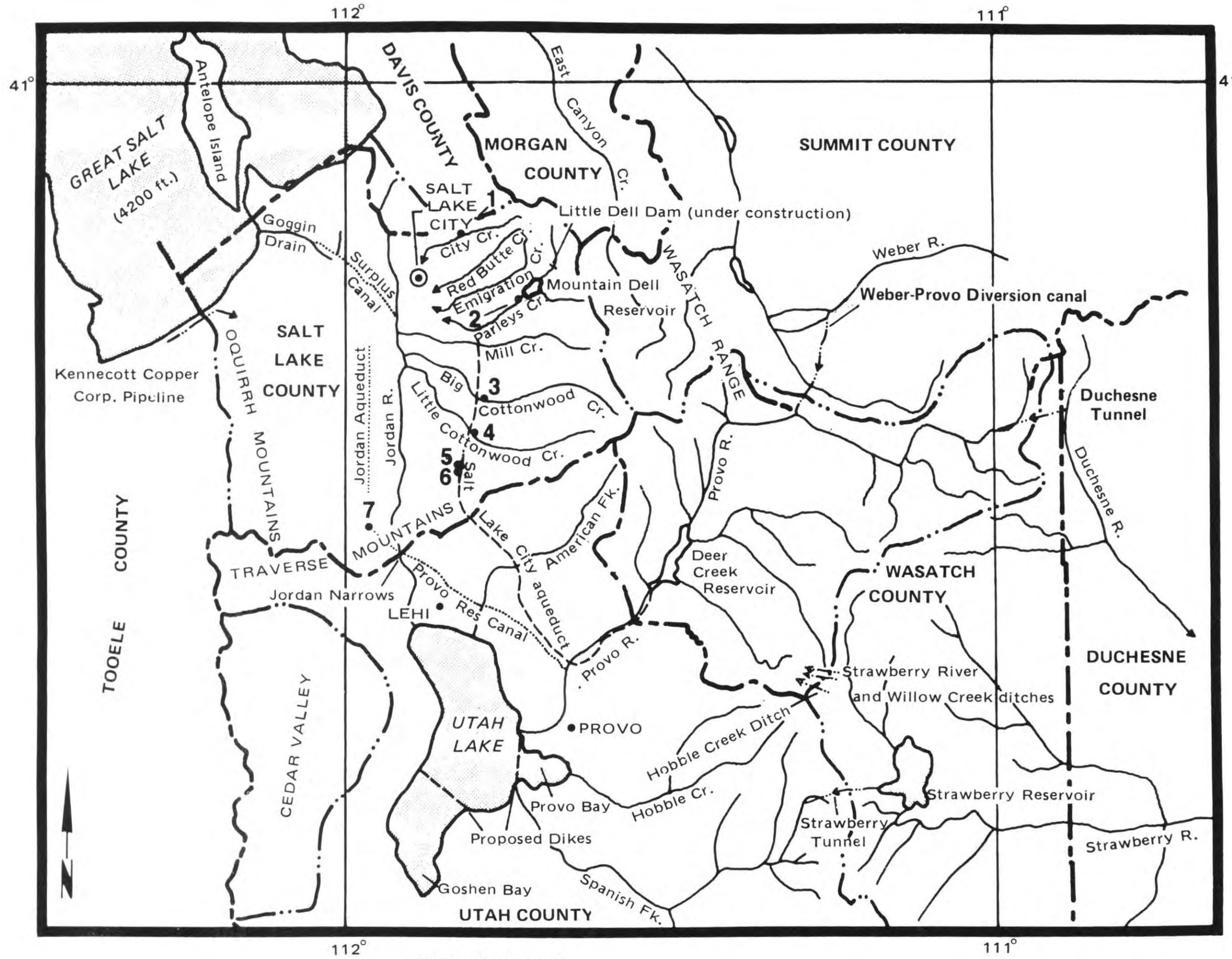
To augment sources in the local canyons, water is imported for municipal use from Deer Creek Reservoir through the Salt Lake Aqueduct and from the Provo River through the Provo Reservoir Canal and Jordan Aqueduct (figure 29). Most of the water obtained through the Salt Lake Aqueduct is treated at the Metropolitan Water Treatment Plant on Little Cottonwood Creek. The west side of the valley is served by the Provo Reservoir Canal and Jordan Aqueduct which deliver water to the Jordan Water Treatment Plant in the southwest corner of the valley (figure 29). Jordan River water is also diverted and treated at this plant. Ground water is pumped for municipal use in Riverton and other west-side cities, and mountain springs supply a part of the ground water used. Canyon communities obtain water from springs and locally from abandoned mine workings and drain tunnels. Domestic water supplies in areas not served by municipal systems are derived from individual wells. Stock water is obtained both from wells and from springs in the Oquirrh Mountains.

The greatest use of water in the Salt Lake Valley is for irrigation, although it is the only category of use which has been declining in recent years (table 5). The Jordan River supplies the majority of

**TABLE 5.**

*Summary of water withdrawals in Salt Lake County (Hely and others, 1971a, 1971b; Coon, King, and Knowlton Engineers, 1982).*

| Uses | Sources | Average Annual Withdrawal (acre-ft) 1964-1968 | 1982 | Percent of Total 1964-1968 | 1982 |
|---|---|---|---|---|---|
| Municipal | Wasatch streams | 53,900 | — | | |
| | Imports | 13,500 | — | | |
| | Ground water | 44,000 | — | | |
| | Subtotal (rounded) | 111,000 | 167,700 | 19 | 25 |
| Domestic/Stock | Ground water | 30,000 | 33,600 | 5 | 5 |
| Industrial | Jordan River | 66,100 | — | | |
| | Imports | 9,500 | — | | |
| | Ground water | 46,700 | — | | |
| | Subtotal (rounded) | 122,000 | 161,500 | 21 | 25 |
| Irrigation | Jordan River | 219,000 | — | | |
| | Wasatch streams | 39,800 | — | | |
| | Imports | 53,600 | — | | |
| | Ground water | 5000 | — | | |
| | Subtotal (rounded) | 317,000 | 294,900 | 55 | 45 |
| All Uses | Jordan River | 285,100 | — | 49 | — |
| | Wasatch streams | 93,700 | — | 16 | — |
| | Imports | 76,600 | — | 13 | — |
| | Ground water | 125,700 | — | 22 | — |
| | Total (rounded) | 580,000 | 657,700 | 100 | 100 |




EXPLANATION

Transmountain Diversion
*Arrows show direction of flow*

Boundary of Jordan River drainage basin

SCALE
0 5 10 15 20 mi
0 5 10 20 30 km

Base from U.S. Geological Survey State base map, 1959, scale 1:500,000

2. • Water Treatment Plants

1. City Creek
2. Parleys
3. Big Cottonwood
4. Metropolitan
5. Southeast Regional
6. Draper
7. Jordan

***Figure 29.*** *The Jordan River drainage basin showing major surface-water elements of the Salt Lake Valley water-supply system (modified from Hely and others, 1971b).*

irrigation water for the valley through various diversions between Utah Lake and Salt Lake City. Nearly all of the Utah Lake water has been diverted from the Jordan River by the time it reaches Sandy City, approximately 15 miles (24 km) north of Utah Lake. However, flow in the Jordan River is replenished by ground water and inflow from tributaries, so that at Salt Lake City, 9 miles (14.5 km) north of Sandy City, the volume of water in the river during wetter parts of the year is only slightly less than at its outlet from Utah Lake (Hely and others, 1971a, 1971b). Water for irrigation is also derived from Wasatch Range streams and the Provo River. The Provo River water is imported from Utah Valley through the Provo Reservoir Canal.

The principal industrial water users in the Salt Lake Valley are the Bingham open-pit copper mine in the Oquirrh Mountains (figure 1) and its associated smelter at Magna. Water for these operations is obtained from Bingham Creek and from streams and springs on the west slope of the Oquirrh Mountains through pipelines and tunnels. Water from the Jordan River is also used at the Magna smelter.

Water for the Salt Lake City metropolitan area is stored in various surface reservoirs (table 6). Discharge from Wasatch Range streams fluctuates both seasonally and on a yearly basis, and the 6000 acre-feet (7.4 million $m^3$) of available water storage is frequently not adequate to contain high stream flows (Coon, King, and Knowlton Engineers, 1982). Some water is thus lost in wet years, and shortages occur during low-flow periods. Some water is stored in small lakes and reservoirs in the Little and Big Cottonwood Creek headwater areas, but only one major reservoir exists on Wasatch Range streams (Mountain Dell Reservoir on Parleys Creek; figures 29 and 30). A small reservoir on Red Butte Creek supplies culinary and irrigation water to Fort Douglas near the University of Utah. Other possible locations for water impoundments on Wasatch Range streams have not been attractive because steep stream gradients and narrow canyons make the cost per unit of storage prohibitive (Hely and others, 1971a, 1971b). At present, the only new storage project authorized on a Wasatch Range stream is the U.S. Army Corps of Engineer's Little Dell Dam on Dell Creek, a tributary to Parleys Creek, just upstream from Mountain Dell Reservoir (figure 29). Little Dell Dam will impound 20,500 acre-feet (25.3 million $m^3$) of water and is scheduled for completion in 1990 (Sefakis, 1987).

**TABLE 6.**
*Capacitities of surface-water storage facilities, Salt Lake City metropolitan water supply.*

| Facility | Principal Use | Storage (acre-feet) |
|---|---|---|
| Existing | | |
| Utah Lake | Irrigation/Industrial | 830,000 (below "compromise" level) |
| Deer Creek Reservoir | All uses | 61,700 (annual allotment) |
| Mountain Dell | Municipal | 3200 |
| Red Butte | Municipal (Fort Douglas only) | 430 |
| Wasatch streams headwaters lakes | Municipal | 2338 |
| Proposed | | |
| Jordanelle Reservoir (Central Utah Project) | Municipal/Industrial | 320,000 |
| Little Dell | Municipal | 20,500 |

Utah Lake, at the headwaters of the Jordan River, has limited usefulness for water storage because it is not allowed to rise above a "compromise" level established in an 1885 agreement (amended in 1983) between Salt Lake County and lakefront property owners. In past dry years, the flow in the Jordan River dropped substantially as the lake level dropped. Flow into Utah Lake is now supplemented through U.S. Bureau of Reclamation transmountain water diversions from the Weber River to the north and the Duchesne and Strawberry Rivers to the east (figure 29). With the increased inflow, the level of Utah Lake can be controlled to maximize storage and maintain constant flow in the Jordan River at 180,000 to 300,000 acre-feet (220 to 370 million $m^3$) per year (Hely and others, 1971a, 1971b). However, at the compromise level, only about 830,000 acre-feet (1.02 billion $m^3$) of water can be stored for use in the Salt Lake Valley, and none of this water is used for municipal purposes.

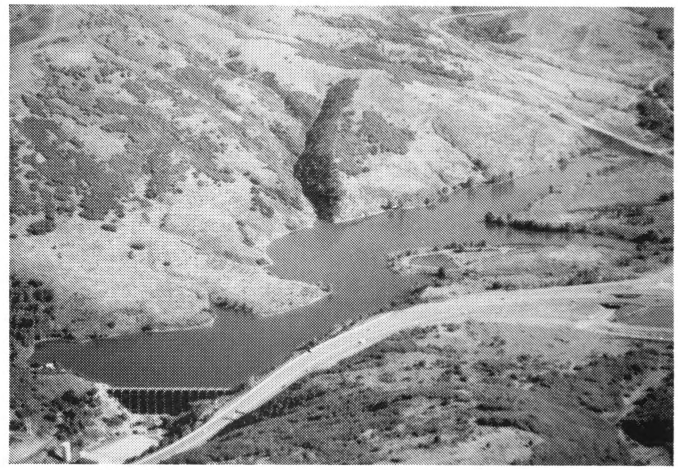


***Figure 30.*** *Mountain Dell Dam and reservoir, a concrete multiple-arch dam on Parleys Creek in the Wasatch Range (photograph credit, G.E. Christenson).*

Water is transported from Deer Creek Reservoir on the Provo River (figure 29) through the Salt Lake Aqueduct and from farther downstream on the Provo River through the Provo Reservoir Canal. The usable capacity of the reservoir is 149,700 acre-feet (184.7 million $m^3$), and it was designed to supply 100,000 acre-feet (123.4 million $m^3$) of water annually. Salt Lake City is entitled to 61.7 percent of the total annual yield from the reservoir, which would be 61,700 acre-feet (76.1 million $m^3$) in a normal year (Coon, King, and Knowlton Engineers, 1982). However, Deer Creek Reservoir has limited value to Salt Lake City for long-term storage because unused portions of the city's annual water allotment cannot always be retained for use in subsequent years.

Saturated, valley-fill deposits in the Salt Lake Valley comprise the largest reservoir in the water-supply system. It has been estimated that about 60 million acre-feet (74 billion $m^3$) of water are present in these deposits, although not all of this water is readily available by conventional pumping (Hely and others, 1971a, 1971b). Studies indicate that an average annual withdrawal of 150,000 acre-feet (185 million $m^3$) of water could be sustained with no permanent reduction in storage. In the period between February/March 1969, and February/March 1983, water-level declines of 0 to 5 feet (0-1.5 m) occurred in the central and northwest parts of the valley (Waddell and others, 1986b). Maximum declines of 5 to 15 feet (1.5-4.5 m) occurred in the southeast part of the valley near the mouths of Little Cottonwood and Bells Canyons due to increased pumping from large public-supply wells. In the remainder of the valley (southwest and northeast), water-level increases of up to 12 feet (3.7 m) were recorded, resulting in a net increase in storage of 33,000 acre-feet (40.7 million $m^3$) for the period (Waddell and others, 1986b).

Water quality is generally good in the deep confined and unconfined aquifers in the Salt Lake Valley (figure 13). The shallow, unconfined aquifer in the central part of the valley and local perched aquifers generally have low transmissivities and poor water quality and have not been extensively developed.

Because of the lack of storage facilities and the restriction placed on the use of water from existing reservoirs, the Salt Lake City area has inadequate long-term water storage, particularly for municipal use (table 6). To help alleviate this problem and supplement water supplies, Salt Lake City will receive water from the Municipal and Industrial System of the Bonneville Unit of the U.S. Bureau of Reclamation's Central Utah Project once that project is complete. The purpose of the Municipal and Industrial System is to collect and store water along the Provo River for use in the Salt Lake City metropolitan area and in northern Utah County. The major project facilities which directly affect Salt Lake City are the Jordan Aqueduct and Jordanelle Reservoir (figure 31). The Jordan Aqueduct has been completed and carries water from the Provo Reservoir Canal to the west side of the Salt Lake Valley. The Jordanelle Reservoir is presently under construction (1990) upstream from Deer Creek Reservoir and will increase storage on the Provo River. Stabilization of reservoir levels in lakes at the river's headwaters in the Uinta Mountains will also be undertaken.

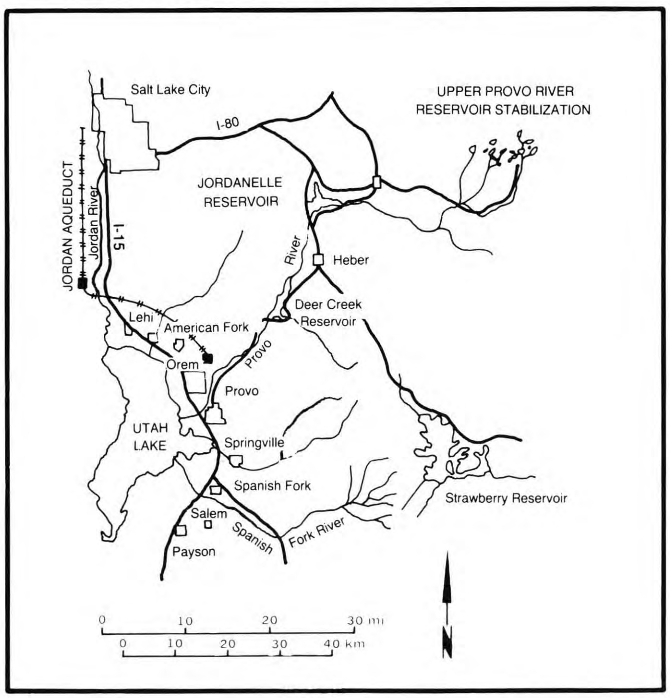



*Figure 31. Features of the Municipal and Industrial System of the Bonneville Unit of the Central Utah Project (from U.S. Bureau of Reclamation, 1978).*

## WASTEWATER

The first sewers in downtown Salt Lake City were installed in the late 1800s, and the city sewer department was founded in 1887 (CH2M Hill, Inc. and others, 1982). About 96 percent of all housing units in the Salt Lake City metropolitan area are served by a public sewer system (Wasatch Front Regional Council, 1975). The sanitary- and storm-sewer systems are separate, but infiltration/inflow (I/I) into the sanitary-sewer system from extraneous sources (ground water, storm runoff) is high. The city's I/I flow in 1981 was 18.8 million gallons (710,000 m$^3$) per day, or about 37 percent of the average daily flow of 50.3 million gallons (190,000 m$^3$) (CH2M Hill, Inc. and others, 1982).

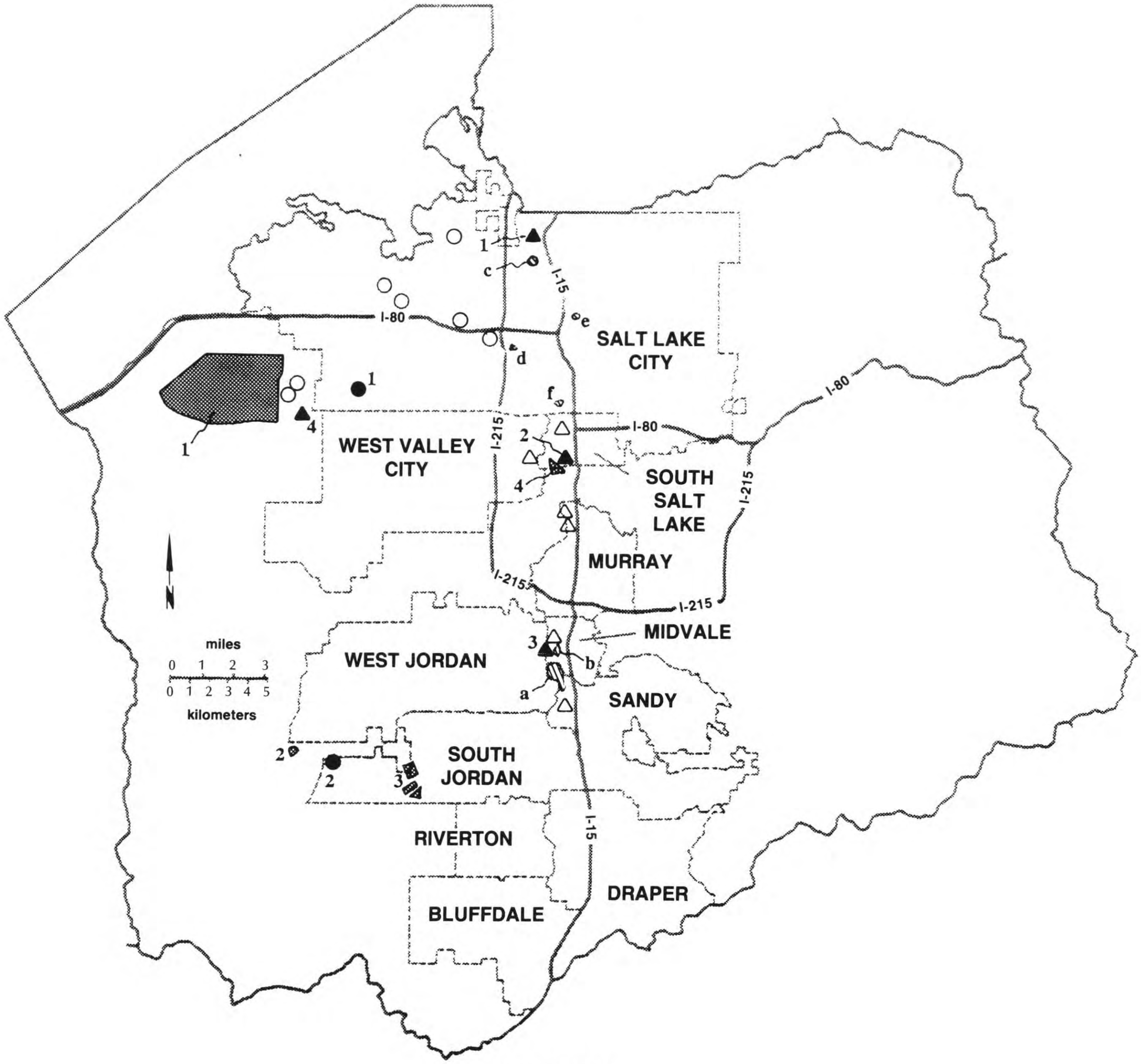
Although much of the valley is served by a sewer system, most Wasatch Range canyons are not. A sewer line has been constructed in Little Cottonwood Canyon to serve the town of Alta and the Snowbird and Alta ski resorts, but other canyons still depend on individual wastewater disposal systems. In Big Cottonwood Canyon, degradation of surface- and ground-water quality has been documented as a result of these practices (Jensen and Lund, 1983), and a sewer has been proposed for the canyon. Although the sewer is controversial because of its potential impact on canyon development, plans are to begin construction in 1990.

Wastewater produced in the Salt Lake City metropolitan area is treated in a variety of municipal and industrial treatment plants before being discharged into either the Jordan River or canals, all of which eventually flow into the Great Salt Lake. Until 1985, nine municipal wastewater-treatment plants served the Salt Lake City metropolitan area (table 7; figure 32). All of the plants were constructed between 1953 and 1965, and some discharge of untreated wastewater into the Great Salt Lake continued until completion of the Salt Lake City Plant (no. 1 on figure 32) in 1965. All of the wastewater-treatment plants were being operated near capacity by 1982 (table 7). To increase capacity, wastewater treatment has been consolidated into four large secondary-treatment plants (table 8; figure 32). The Salt Lake City Plant has been expanded to serve the northern part of the valley. A new Central Valley Plant has replaced the Granger-Hunter, South Salt Lake, Cottonwood, Murray, and Salt Lake City Suburban #1 Plants, and the new South Valley Plant has replaced the Tri-Community (Midvale) and Sandy City Plants. The Magna Plant will be retained and is being upgraded to increase capacity.

**TABLE 7.**

*Salt Lake County wastewater-treatment plants (Utah Department of Health, 1973; Coon, King, and Knowlton Engineers, 1982).*

| Year Operation Began | Community or District | Design Capacity (mqd) | 1982 Average flows (mqd) |
|---|---|---|---|
| 1953 | Murray | 5.0 | 3.0 |
| 1954 | South Salt Lake | 4.6 | 4.3 |
| 1955 | Salt Lake City Suburban #1 | 16.0 | 15.7 |
| 1956 | Tri-Community Midvale | 7.8 | 7.7 |
| 1958 | Salt Lake City Cottonwood | 8.0 | 8.0 |
| 1959 | Granger-Hunter | 7.0 | 8.7 |
| 1962 | Sandy | 4.0 | 2.6 |
| 1962 | Magna | 1.3 | 1.2 |
| 1965 | Salt Lake City | 45.0 | 36.0 |
| | Total | 98.7 | 87.2 |




EXPLANATION

1▲ Wastewater-treatment plants (new and upgraded)
1. Salt Lake City
2. Central Valley
3. South Valley
4. Magna

△ Abandoned or soon-to-be abandoned wastewater-treatment plants

1● Active landfill sites
1. City-County landfill
2. Transjordan landfill

○ Abandoned landfill sites (Jensen, 1981; Waddell et al., 1986b)

1 Mining waste and UMTRA sites
1. Kennecott tailings pond
2. Kennecott Bingham reservoir
3. Kennecott evaporation ponds
4. Vitro UMTRA site

a Superfund sites
a. Sharon Steel
b. Midvale slag
c. Rose Park sludge pit
d. Portland Cement
e. UP&L/American Barrel
f. Wasatch Chemical

***Figure 32.*** *Wastewater-treatment plants, sanitary landfills, mining waste sites, and Superfund sites in the Salt Lake City metropolitan area.*

**TABLE 8.**
*New and proposed upgraded Salt Lake County wastewater-treatment plants (Bhayani, 1982, 1987).*

| Year Operation Began or Scheduled | Plant | Population designed to be served | Design Average flow (mqd) |
|---|---|---|---|
| 1987 | Salt Lake City Expansion | 475,000 | 56 |
| 1992 | Additional Plant | ---- | 16 |
| 2000 | Additional Plant | ---- | 16 |
| 1987 | Central Valley | 420,000 | 50 |
| 1987 | South Valley | 255,000 | 25.5 |
| | TOTAL (1987) | 1,150,000 | 131.5 |

Sludge generated at the older plants was generally dried in asphalt-lined drying beds to about the consistency of peat, stacked on-site for one year, and then sold or given away for fertilizer (Bhayani, 1982). At the Salt Lake City plant, sludge is utilized as fertilizer on nearby farms (Bhayani, 1987).

Most major industries in the Salt Lake City metropolitan area operate consumptive pre-treatment facilities for wastewater renovation. Water not consumed in the pre-treatment process is introduced into the municipal sewer systems. Kennecott Utah Copper Corporation operates a variety of settling, evaporation, and seepage ponds at its concentrators and precipitation plants. Oil refineries operate grease removal or skimming tanks and oxidation ponds. Settling ponds are used by most sand and gravel companies for treatment of wastewater.

## SOLID AND MINING WASTES

In 1990, residents in the Salt Lake City metropolitan area produced 6.2 pounds (2.8 kg) of solid waste per capita per day for an annual total of about 1.3 million tons (1.2 million tonnes) of solid waste for landfill disposal (Diamant, 1991). Two municipal sanitary landfill sites are presently in operation in the Salt Lake City metropolitan area (figure 32). One is in the Magna area in the northwest part of the Salt Lake Valley (City-County Landfill) and the other is in the Copperton area in the southwest part of the valley (Transjordan Landfill). Salt Lake City and County jointly operate the City-County Landfill, which handles about 90 percent of the municipal solid waste produced in the Salt Lake City metropolitan area (Diamant, 1991). The Transjordan Landfill is operated by the cities of Sandy, Murray, West Jordan, and Midvale. In addition to these two municipal landfills, solid wastes produced in the Salt Lake Valley are disposed in two construction/demolition-debris landfills and several private landfills operated by waste-producing companies (Diamant, 1991).

The City-County Landfill opened in 1982 and has a projected life of about 20 years. The previous sanitary landfill, which is now closed, was about 2 miles (3.2 km) to the west near Kennecott's Magna tailings pond (figure 32). Both sites are founded on fine-grained Lake Bonneville sediments, principally clay with silt and sand stringers. At the new site, the ground-water surface is at about 10 feet (3 m) of depth, and cells are excavated to within 2-3 feet (0.6-0.9 m) of that level. The clays act as a natural liner to minimize infiltration of leachate into the ground water, and compacted earth barriers and a leachate collection system have been installed to further retard migration of leachate. Observation wells have been placed both up- and down-gradient from the old and new City-County Sanitary Landfill sites to monitor ground-water quality. No degradation has been detected (Bauer, 1987).

The Transjordan Landill is adjacent to Bingham Creek downstream from the Bingham mining district. It has been in operation for about 23 years and has space available for an estimated 25 additional years. Although located in a flood plain, the flood hazard is low due to control of flow in the creek for mining activities upstream (Kennecott, 1984a). Soils at the site are chiefly alluvial gravels which locally contain clay lenses. However, none of the clay lenses are extensive enough to seal the bottom of the landfill (Rollins, Brown, and Gunnell, Inc., 1978), and soils are highly permeable. Ground water is at a depth of over 200 feet (61 m) below the landfill. Monitoring wells have indicated degradation of ground-water quality in the area (Hely and others, 1971a; Waddell and others, 1986a; Kennecott, 1988), but it is not known to what extent, if any, the landfill may be contributing to this degradation.

Operators of both sanitary landfills are considering resource recovery (recycling) and methane production to enhance revenues and increase the storage capacities of the two facilities. Recycling is underway, but present economics for methane recovery are not favorable. Attempts are being made to zone a large block of land near the City-County Landfill for future landfill sites and compatible industries which may ultimately provide a market for resources recovered from the landfills (Stewart, 1983). Many abandoned "landfills" and dumpsites are present in the north Salt Lake City area (figure 32) and along the Jordan River. Some of the sites are partially below the ground-water surface and are known to contain materials such as cement kiln dust and refinery wastes (Bardwell, 1987). Monitoring wells have been placed at many of these sites to evaluate the threat to ground-water quality (Waddell and others, 1986a).

Mining has been active in the Oquirrh Mountains since the late 1800s, and the principal ore body is found in the Bingham Canyon area at the south end of the range. A large, open-pit copper mine is operated there with a smelter and tailings ponds located at Magna near the south shore of the Great Salt Lake (figure 32). Storage of leach process water in Bingham Reservoir and disposal of excess mine water in evaporation ponds east of Copperton (figure 32) have resulted in ground-water contamination over a several square-mile area (Fisk and Clyde, 1981; Waddell and others, 1986; Kennecott, 1988). A plume of ground water with relatively high concentrations of total dissolved solids has been detected downgradient from Bingham reservoir (Hely and others, 1971a; Waddell and others, 1986a; Kennecott, 1988). Sulfate and heavy metal (iron, copper, arsenic, selenium, cadmium, cobalt, chromium, nickel, and/or zinc) concentrations are also locally high, as shown by the results of a five-year study of ground-water quality downgradient from the mine (Kennecott, 1988).

The tailings pond at Magna covers about 7 miles$^2$ (18 km$^2$), and ground water in the area is high in total dissolved solids and arsenic. However, the source of the contamination has not been definitely traced to the tailings pond because the ground water in the area is naturally of poor quality (Fisk and Clyde, 1981). During a temporary closure of the mine and smelter in 1985-1986, the pond was not used and tailings dust blown from the dry pond was dispersed off-site, creating "tailings storms" during high winds which reduced visibility. A water dispersal system was emplaced along the perimeter of the tailings pond in 1988 to eliminate the problem of blowing dust in the area.

## UMTRA SITE

Stabilization of uranium mill tailings was given special treatment by Congress in the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978. The U.S. Department of Enery has been given the responsibility of selecting and executing remedial action plans at uranium mill tailings remedial action (UMTRA) sites identified under Title 1 of the UMTRCA. One such UMTRA site (Vitro) is about 4 miles (6.4 km) south of downtown Salt Lake City (figure 32).

A uranium mill was operated at this site by the Vitro Chemical Company from 1951 to 1968. The plant processed uranium ores from 1951 to 1964 and was converted to vanadium production in 1965 (Ford, Bacon, and Davis Utah, Inc., 1976). It continued to operate until 1968 and was dismantled by 1970. Tailings were placed on grade within dikes constructed with material borrowed at the site. The tailings, consisting of very fine sand, clay, and other by-products of milling, remained uncovered and subject to wind and water erosion. Precipitation infiltrating into the tailings piles leached radioactive materials and transported them to shallow ground-water. In addition, the base of the tailings were locally several feet below the present ground-water surface (Ford, Bacon, and Davis Utah, Inc., 1976). Increased total dissolved solids, chloride, sulfate, iron, and uranium have been detected in shallow ground water beneath the site and downgradient to the Jordan River, where the contamination plume extends downstream along the river for 5000 to 6000 feet (1500-1800 m) (Waddell and others, 1986a).

Tailings were removed from the site and used as fill at various locations in the general site vicinity. Surveys by the EPA (Duncan and Eadle, 1974) to detect gamma radiation, radon gas, and various radon daughter products delimited 71 anomalies in the site vicinity; 40 of the anomalies were considered sufficiently hazardous to reguire remedial action (Ford, Bacon, and Davis Utah, Inc., 1976). Tailings have been carried downstream by Mill Creek and other Jordan River tributaries which drain the site, and land adjacent to the site has been contaminated by windblown tailings. Various remediation alternatives to mitigate the hazard were proposed, and it was decided to move the tailings to a designated landfill disposal site 85 miles (137 km) west of Salt Lake City, in Tooele County. Removal of the 2.8 million yards$^3$ (2.1 million m$^3$) of material began in January, 1985 and was completed in November, 1986 at a total cost of $53 million (Day, 1989). Fill removal and clean-up of the tailings used off-site cost an additional $14 million. Granular material was brought in to fill and level the site, which is now used by the Central Valley Wastewater Treatment Plant and leased for other industrial uses.

## SUPERFUND SITES

As of February, 1991, six sites in the Salt Lake Valley (figure 32) are on the Environmental Protection Agency's (EPA) Superfund National Priority List (NPL): 1) Sharon Steel, 2)Midvale slag, 3) Rose Park sludge pit, 4) Portland Cement, 5) UP&L/American Barrel, and 6) Wasatch Chemical (figure 32). Much of the information in the following discussion on individual waste sites was obtained from fact sheets and interviews with personnel of the EPA and Utah Department of Environmental Quality (formerly Utah Division of Environmental Health).

The Sharon Steel and Midvale slag sites, located along the Jordan River in Midvale (figures 32 and 33), have a long history of ore-processing activities. A variety of companies operated copper smelters in the area from 1899 to 1907, when the smelters were closed because of their deleterious effect on agriculture in the valley (Hansen, 1963; Nackowski, 1964). Even though copper smelting was prohibited, a lead-silver-zinc smelter continued to operate until 1958. Milling operations continued until 1971. Although all mining-related activities have ceased, mill tailings (Sharon Steel site) and slag, baghouse dust, and dross (Midvale slag site) remain in what has become a densely populated part of the Salt Lake City metropolitan area. Tailings at the Sharon Steel site (figure 33) contain elevated levels of lead, arsenic, cadium, and other metals, and have contaminated soil, air, and ground-water. These tailings are periodically treated with a dust suppressant to reduce wind-blown particulate emissions. Sampling at the Midvale slag site (figure 32) indicated that the slag contains high levels of arsenic, lead, cadmium, and zinc. Shallow ground water at the site is contaminated, and there is concern that the deeper aquifers may be affected. Both the tailings and slag sites have been fenced to restrict access.

Several oil companies operate refineries in the northern part of the Salt Lake City metropolitan area. Until recently, wastes produced by the refining process were disposed of on-site in unlined ponds or through land application in nearby areas. Most ponds are now closed and wastes are shipped to a commercial hazardous-waste disposal facility west of Salt Lake City (Verbica, 1987). All

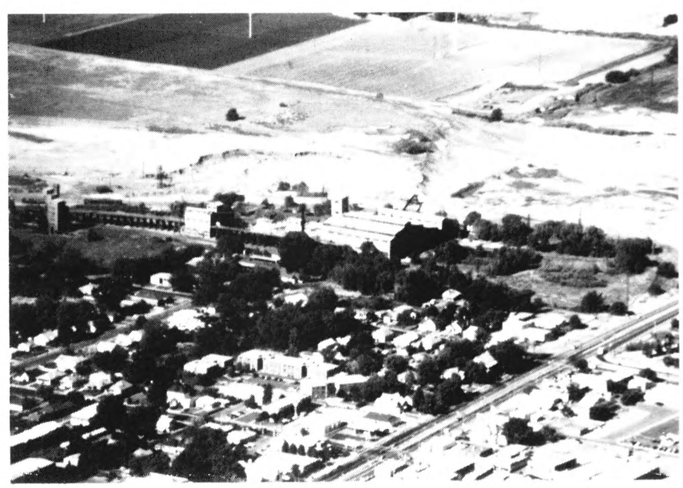


***Figure 33.*** *Tailings and abandoned buildings at the Sharon Steel site on the Jordan River (photograph credit, G.E. Christenson).*

refineries are now required to monitor ground-water quality because leakage from ponds and settling basins, and surface spills have contributed to ground-water contamination in the area (Fisk and Clyde, 1981). This contamination has caused numerous porblems off-site. In one case, pollution affected a residential area near the abandoned Rose Park oil refinery sludge pit (figure 32). Contamination of ground water by oil and grease and a build-up of gaseous hydrocarbons were documented at the sludge pit (McMillan, 1978), and a slurry wall was constructed around the site and a compacted clay cap (final cover) was installed over the pit to contain wastes and prevent further ground-water contamination. Similar procedures are being followed during closure of waste ponds at operating refineries, but the number of abandoned sites, similar to the Rose Park sludge pit, is unknown (Verbica, 1987).

The first cement plant in Utah was built in 1891 in Salt Lake City by the Portland Cement Company of Utah (Romney, 1963). In 1979, Portland Cement was purchased by Lone Star Industries. The principal waste product of the cement-making process is cement kiln dust (CKD). This waste is a caustic alkaline material that may burn or chafe skin on contact, and contains heavy metals in trace quantities. CKD disposal has occurred at various sites in northwest Salt Lake City. The largest site received CKD from 1963 to 1983, and has been placed on the Superfund NPL (figure 32). Remedial investigation and feasibility studies have been completed. High pH and elevated levels of heavy metals were found in the shallow ground water beneath the site. The CKD has been treated with a vinyl acrylic resin dust suppressant and will be excavated and disposed of in a lined industrial landfill.

Abandoned chemical or chemical-waste storage and disposal sites in Salt Lake City have been identified in recent years as potential environmental hazards. Those on the Superfund NPL include the UP&L/American Barrel and Wasatch Chemical sites (figure 32). A creosote wood-treating facility was operated at the UP&L/American Barrel site by Utah Power and Light in the early 1940s. From sometime in the 1950s to 1988, the American Barrel company leased the site for storing used steel drums scheduled for recycling. Compounds found in the soil at the site include industrial solvents, pesticides, coal tars, and heavy metals, and shallow ground water is contaminated. Contamination of soil and ground water by organic solvents has been documented at the Wasatch Chemical site, a chemical production operation (figure 32) (Verbica, 1987).

## WETLANDS

Approximately 70,000 acres (28,000 ha) in the northwest part of the Salt Lake Valley are classified as wetlands, together with 2000 acres (800 ha) along the Jordan River and its tributaries. The majority of wetlands in the northwest part of the valley are saline and border the Great Salt Lake or are in the Jordan River delta area. Fresh-water wetlands occur along the Jordan River and its tributaries and in discharge areas of shallow perched aquifers and leaking canals (West, 1984). Wetlands provide a variety of benefits in the Salt Lake Valley including: 1) flood control, chiefly in floodplain areas where flood waters are temporarily stored as they spread out and slow; 2) wildlife habitat, chiefly for migratory waterfowl; 3) water quality and pollution control, particularly for urban storm-water runoff; 4) parks and recreation; 5) ground-water recharge and discharge; and 6) shoreline anchoring and sediment trapping.

Much of the wetland area along the Jordan River and its tributaries has been developed, although some remains as vacant lots, open fields, and pastures. In the Jordan River delta area and adjacent to the Great Salt Lake, wetlands are extensive and consist of open saline water and saline marshes, meadows, flats, plains, and playas (West, 1984). They are interrupted by the Salt Lake City International Airport and various streets, highways, landfills, waste-disposal sites, and tailings ponds. Much of the remaining area has been annexed by Salt Lake City for residential, commercial, and industrial uses, and the airport has plans for expansion (West, 1984). Wetland areas were considerably reduced by the rise of the Great Salt Lake from 1983 to 1985.

A pilot project sponsored by Salt Lake County is underway along the Jordan River to treat storm-water effluent by draining it across an artificially improved wetland (Jensen, 1989). Constructed wetlands elsewhere in the Salt Lake Valley are being studied for similar use. In some cases, wetlands are being incorporated into landscaping plans to treat local runoff before discharging it into streams (West, 1984). Wetlands in the northeast part of the valley provide protection against flooding of the Great Salt Lake. Destruction of structures which have been built on these wetlands by lake flooding demonstrates one of the risks associated with development adjacent to the lake. Wetlands also aid in controlling the level of the Great Salt Lake through evapotranspiration of surface and shallow ground water.

## OTHER ENVIRONMENTAL CONCERNS

Sources of surface-water and shallow ground-water contamination in the Salt Lake City metropolitan area, not related to waste disposal, include leaking underground storage tanks and irrigation water. The Utah Division of Environmental Health is attempting to inventory underground storage tanks and reported leaks statewide. Approximately 3700 underground storage tanks have been identified in the Salt Lake City metropolitan area. Eighty-five percent of the tanks are steel, 20 percent are more than 20 years old, and only 18 percent are cathodically protected against corrosion (Mortensen, 1987). Consequently, corrosion is the principal cause of leaks. The majority of leaks have been in gasoline and diesel tanks at service stations, with an average of 10 leaks per year reported to health authorities in the Salt Lake City metropolitan area (Mortensen, 1987).

The environmental effects of gasoline leaks include fumes in homes and businesses, ground-water contamination, and sewer infiltration. Gasoline leaks have caused evacuations at the Salt Lake City International Airport, six units of a Salt Lake City apartment building, four Salt Lake City businesses, and an entire block in the business district of West Valley City (Mortensen, 1987). Leaks have the greatest impact in areas of shallow ground water, where gasoline collects at the ground-water surface and then percolates into sewers or other buried utility lines.

Much of the irrigation water in the Salt Lake Valley comes from the Jordan River. Pollutants entering Utah Lake, which is the source of the Jordan River, are concentrated due to high evaporation losses from the shallow lake. Water in the Jordan River is thus of marginal quality as it enters the Salt Lake Valley. Further concentration of pollutants occurs as the river water is used for irrigation, and fertilizers and soil additives are leached from the fields as the water percolates to the shallow ground water. Shallow ground water in agricultural areas is commonly very high in total dissolved solids (Hely and others, 1971a). In its lower reaches, the Jordan River acts as a drain for irrigation return flow and shallow ground-water seepage. Consequently, water quality in the river deteriorates in a downstream (northward) direction, but restoration of wetlands is expected to assist in reducing downstream pollution.

The occurrence of natural combustible gas, chiefly methane, is an environmental hazard in the north part of Salt Lake City. This gas presents a fire and explosion hazard if concentrations are sufficiently high. The gas is probably generated from decomposition of organic material in fine-grained, near-surface Quaternary sediments, although upward migration of the gas from a deeper source cannot be discounted (Kaliser, 1976). The gas migrates into sandy layers which act as reservoirs when overlain by fine-grained deposits. Several zones of gas accumulation have been encountered in wells, and the highest concentrations of gas emitted at the surface occur in marshes bordering the Great Salt Lake. North of Salt Lake City near Farmington Bay, approximately 25 shallow wells were drilled in 1895 to collect gas for use in the city. The project was short-lived because reserves were quickly depleted, and after 19 months of operation the wells were abandoned (Kaliser, 1976).

# USE OF UNDERGROUND SPACE

*Douglas A. Sprinkel*

Significant use of underground space in the Salt Lake City metropolitan area is confined to the mountains southeast and southwest of the city (figure 34). Use of space varies from storage of documents and valuables to transportation of water and materials. Most of the space has been converted from old metal-mine workings in the Little Cottonwood and Bingham mining districts, which were originally developed in the late 1800s and early 1900s. The only newly created underground space consists of two large storage vaults in Little Cottonwood Canyon.

Use of underground space in Salt Lake City will probably continue to be restricted to the Wasatch Range and Oquirrh Mountains. These areas provide a variety of suitable host rocks, are in close proximity to the city, and have minimal problems associated with ground water. Development of underground space in the Salt Lake Valley will likely not occur in the near future because of shallow ground-water problems and concerns about the seismic hazards associated with valley-fill deposits.

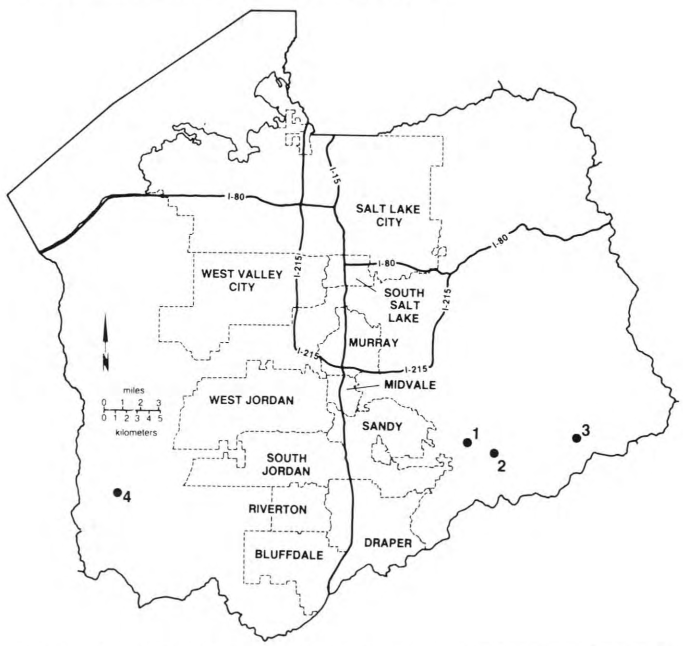



***Figure 34.*** *Salt Lake City metropolitan area with locations of currently utilized underground space: 1) Granite Mountain Records Vault, 2) Perpetual Storage, Inc. storage vault, 3) Little Cottonwood mining district, 4) Bingham mining district.*

## NEW UNDERGROUND SPACE

Two storage vaults were constructed in the 1960s in the Wasatch Range about 20 miles (32 km) southeast of Salt Lake City (figure 34). The Granite Mountain Records Vault was constructed for and is operated by the Genealogical Society of The Church of Jesus Christ of Latter-day Saints. The other vault is a commercial facility owned and operated by Perpetual Storage, Inc. The purpose of both storage vaults is to provide maximum protection from both natural and man-made hazards, including nuclear explosions, for valuable records and property.

## Granite Mountain Records Vault

The primary purpose of this vault is to store genealogical records and church-related documents. Four sites were originally considered for the vault, but the Granite Mountain location was selected on the basis of pre-established design criteria that included: 1) a location within 25 miles (40 km) of the LDS Church Administration Building in Salt Lake City, 2) at least 250 feet (76 m) of overburden above the vault area, 3) geologically suitable conditions for construction and maintenance, and 4) availability of water, sewer, and electric service.

Work at Granite Mountain began in 1958 with a 500-foot (152 m) exploratory boring followed by a pilot tunnel to evaluate host-rock suitability. Actual construction commenced in 1961, and the project was completed in 1965 at a cost of nearly $2 million. The vault was tunneled into quartz monzonite of the Little Cottonwood stock (figure 35). This relatively homogeneous intrusive igneous body proved to be structurally uncomplicated. No faults or extensive fracture systems were encountered. The initial tunnel was dry to the 500-foot (152 m) station where seepage was encountered. A horizontal exploratory boring was made to determine the extent of the water problem. The boring continued to intercept water for 150 feet (46 m). The flow was about 2 gpm (7.6 liters per minute). The decision was made to construct the storage vaults in the dry portion of the quartz monzonite and to develop the seep for the facility's water supply (Clayton, 1987). The exploratory boring was reamed and a concrete reservoir was constructed (figure 36). Excess water is discharged to Little Cottonwood Creek. The only major geotechnical concern at the Granite Mountain site was the potential for spalling of boulder-size bedrock slabs, as rock falls, from the mountain face above the facility. This hazard was partially mitigated by extending the entrance and receiving dock away from the mountain front; however, falling boulders have damaged vehicles parked outside of the vault portals.

All vault tunnels are lined with eight-gauge corrugated steel arches (figure 37) and grouted with 18 inches (46 cm) of concrete (Church of Jesus Christ of Latter-day Saints, undated). The floors consist of a double concrete layer separated by a waterproof membrane. The vault provides space for offices, a microfilm processing laboratory, six storage areas with corridors and access tunnels, and a water reservoir (figure 36). Each of the six storage rooms can accommodate 885,400 rolls of 35 mm microfilm, giving a total vault capacity equivalent to 25 million 300-page volumes of text. The storage rooms are protected by a 14-ton (12.7-tonne) door and two 9-ton (8.2-tonne) doors (figure 36). The facility has its own generator in case of an electrical outage. Outside air is pumped in, filtered, and circulated through the facility. The air temperature in the vault remains a constant 57°F (13.9°C) and is not regulated except in office and laboratory areas. Humidity is near 50 percent and must be regulated to maintain ideal archival conditions.

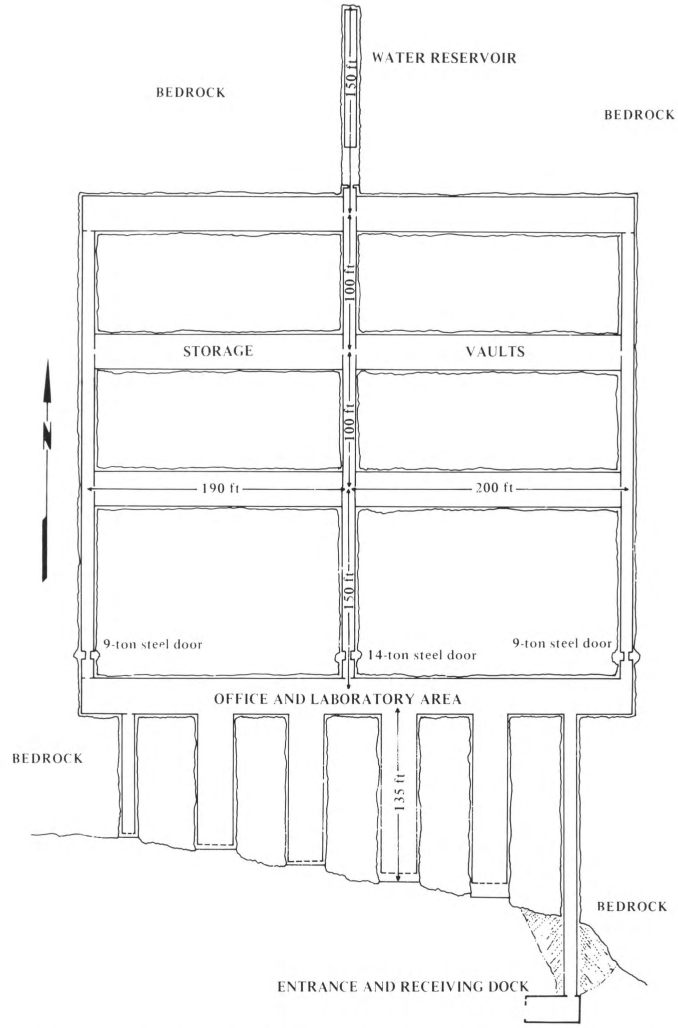



***Figure 36.*** *Plan view of the Granite Mountain Records Vault (modified from Church of Jesus Christ of Latter-day Saints, undated).*

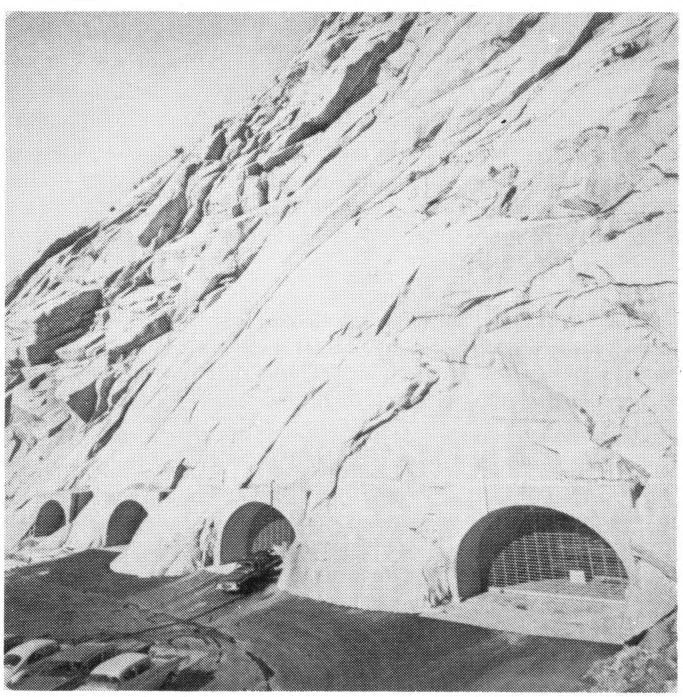


***Figure 35.*** *Auxiliary access tunnels to the Granite Mountain Records Vault in Little Cottonwood Canyon (photograph credit, N.W. Clayton).*

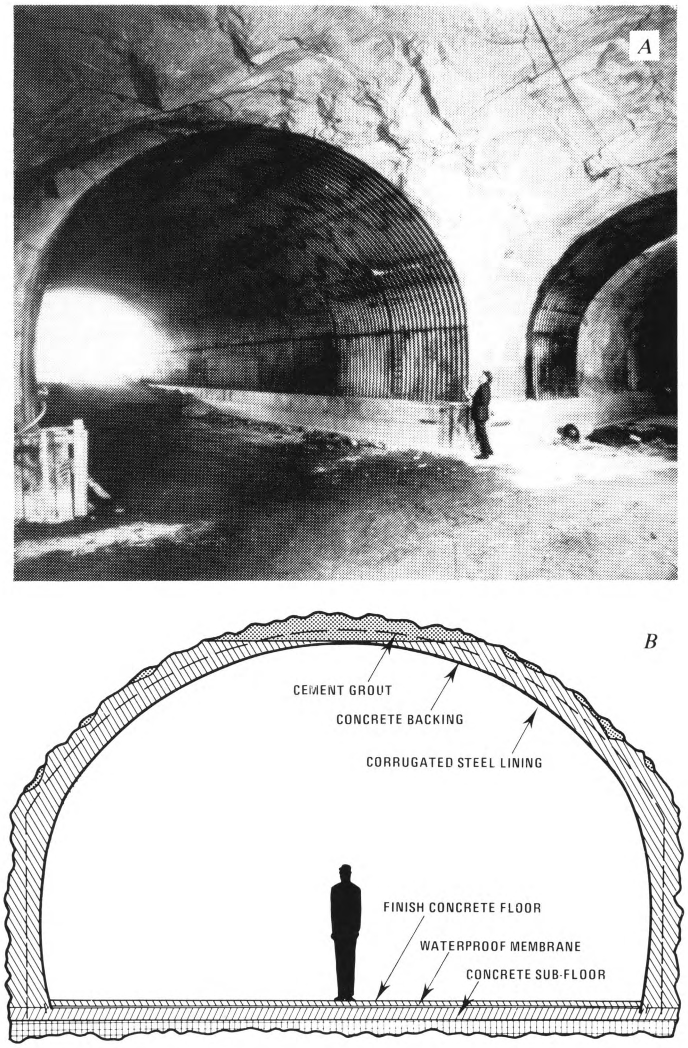



***Figure 37.*** *A) Granite Mountain Records Vault tunnels during construction prior to installation of corrugated steel lining (photograph credit, N. W. Clayton). B) Diagrammatic cross section showing a typical record storage room (from Church of Jesus Christ of Latter-day Saints, undated).*

### Perpetual Storage, Inc. Vault

The Perpetual Storage, Inc. (PSI) vault provides commercial space for storage of private, industry, and government records. Construction of the vault began in 1967 and was completed the same year. Construction took less time than the Granite Mountain Records Vault because the PSI vault is smaller and because the same contractor employed by the LDS Church was used, thereby taking advantage of the experience gained on the church project. The geology of both sites is similar; however, the initial location selected for the PSI facility proved unsuitable because of an unstable talus slope. A new site was chosen nearby where bedrock crops out at the surface.

The PSI vault consists of only one main room and access tunnel. The security and work offices and the bulk storage area utilize a multi-level construction scheme in front of the main security vault. The vault and access tunnel are lined with ungrouted, arched, double-corrugate steel panels and the concrete floors are separated from bare rock by a water-tight, neoprene liner. The approximate floor space of the vault and offices is 8400 feet$^2$ (780 m$^2$). Water demand for the facility is approximately 100 gpd (380 liters per day). Water is collected from seeps within the facility and is stored in a 6000 gallon (22,712 liter) tank beneath the security office. Excess water is discharged to Little Cottonwood Creek. Electrical power is supplied by a hydroelectric plant on Little Cottonwood Creek. Air is pumped into the facility and is carefully monitored to maintain optimum archival storage conditions.

## CONVERTED UNDERGROUND SPACE

Two areas near Salt Lake City presently use a significant amount of converted underground space. Both are located in former or active mining areas, the Little Cottonwood and Bingham mining districts (figure 34). All of the space was created by mining operations, either for ore removal or mine dewatering.

### Little Cottonwood District

Snowbird Ski Resort, the largest resort in Little Cottonwood Canyon, required a larger and more reliable source of culinary water and expanded fire-fighting capability before a proposed expansion could take place. The Wasatch Drain Tunnel and the Hellgate Mine were converted into a 30-million gallon (113,340 m$^3$) underground water-storage facility by installing watertight bulkheads near the tunnel portals (Eckhoff, Watson, and Preator Engineering, 1985; Intermountain Contractor, 1986). Ponding water behind the bulkheads increased the volume of water available during periods of peak demand and met fire-fighting requirements. Pumps and a network of water lines connect the two underground reservoirs with existing surface storage and distribution facilities. The $1.5 million project cost less to construct than a conventional 3-million gallon (11,300 m$^3$) surface concrete storage tank (Intermountain Contractor, 1986). Furthermore, because of natural pressurization behind the bulkheads, the project will provide an estimated annual savings of $20,000 in pumping costs (Eckhoff, Watson, and Preator Engineering, 1986).

### Bingham District

Although much has been written about the geology and history of the Bingham mining district and the Kennecott Utah Copper Corporation's open-pit mine, little specific information is available on past or present utilization of underground space in the mining district. Early mining activities were restricted to underground operations (Arrington and Hansen, 1963), and many mines encountered ground water. It is uncertain whether tunnels were driven specifically to dewater the mines. However, it is believed that some lower mine workings were eventually abandoned and used as drains to keep the upper mines dry. Many early mines were exhumed with the introduction of open-pit mining in 1907 (Arrington and Hansen, 1963). Five of the underground workings that remain are presently used in conjunction with open-pit operations for ore haulage or water drainage. Total length of the five tunnels exceeds 42,000 feet (12,800 m).

# MINERAL AND ENERGY RESOURCES

*J. Wallace Gwynn and Bryce T. Tripp*

The development of Salt Lake City has been heavily influenced by an abundance of nearby mineral resources, including salines and minerals from the Great Salt Lake, metallic minerals in neighboring mountain ranges, and industrial rocks and minerals. Geothermal resources are also utilized to a limited extent.

## SALINES

The Great Salt Lake, a modern-day remnant of Pleistocene Lake Bonneville, is a highly saline, terminal lake containing 4 to 5 billion tons (3.6 to 4.5 billion tonnes) of dissolved salts. During historical time, the lake has fluctuated from a high of 4211.85 feet (1283.79 m) in 1986 to a low of 4191.30 feet (1277.52 m) in 1963. Through these changes, the approximate area of the lake has ranged from 610,200 acres (246,900 ha) to 1.472 million acres (595,700 ha). The lake's volume has ranged from 8.685 million acre-feet (10.7 billion $m^3$) to 30.46 million acre-feet (37.5 billion $m^3$), and the lake's salinity has ranged from 5 to 27 percent. A rock-fill causeway, built in an east-west direction across the lake in 1959 by the Southern Pacific Railroad, divides the lake into two parts. The southern part, into which all of the lake's major tributaries flow, occupies about 60 percent of the lake's total area. The presence of the causeway has caused the salinity of the southern part of the lake to decrease relative to the northern part. Currently (Spring 1990), the 9 percent salinity of the southern part is about one half that of the northern part.

Sodium chloride (common table salt) was obtained from the lake by early explorers even before Mormon pioneers settled in the Salt Lake Valley. Following settlement, the pioneers either gathered natural crystalline salt from the shores of the lake or produced salt by boiling the lake brine in large kettles. Since that early time, sodium chloride has been the principal salt produced from the lake. From 1980 through 1986, an average of more than 1 million tons (910,000 tonnes) of salt were produced per year by as many as five companies. The companies include Morton Salt, American Salt, Sol-Aire Salt and Chemical, Lake Crystal Salt, and Great Salt Lake Minerals and Chemicals. Large-scale, solar-evaporation pond complexes have been built (figure 38), harvesting equipment developed, and fortunes made and lost as markets for salt changed, or as the lake level fluctuated. The recent rise in the lake level, which started in 1983 and peaked in 1987, made the production of salt from the lake difficult, due to flooding of evaporation ponds and subsequent dilution of the brine.

Other products that are or have been extracted from the lake include magnesium metal, chlorine gas, magnesium chloride brine, and potassium and sodium sulfate. Before its evaporation pond dikes were breached by the rising level of the Great Salt Lake, the Renco Group, Inc. (formerly AMAX Magnesium Corp.) magnesium plant could produce up to 45,000 tons (41,000 tonnes) of magnesium metal per year (Toomey, 1974) from brines in the southern part of the lake. The Great Salt Lake Minerals and Chemicals Corporation facility, utilizing the more concentrated brines in the north part of the lake, produced 240,000 tons (220,000 tonnes) of potassium sulfate, 150,000 tons (140,000 tonnes) of sodium sulfate, and up to 600,000 tons (540,000 tonnes) of magnesium chloride per year (Great Salt Lake Minerals and Chemicals Corp., undated) until 1986, when a break in an outer dike flooded their entire solar evaporation complex. Production of potassium sulfate did not resume until 1989. The production of each of these commodities involves the initial concentration of the lake water, through the process of solar evaporation, to obtain the desired salts or concentrated brines. These salts and brines are then processed to make the final products. Magnesium metal and chlorine gas are produced by the electrolytic reduction of anhydrous magnesium chloride. Potassium sulfate is produced by the selective leaching of potassium-magnesium salts; anhydrous sodium sulfate is produced by the conversion of mirabilite ($Na_2SO_4 \cdot 10\ H_2O$); and magnesium chloride brine is produced through the concentration of brines and the associated precipitation of potassium and magnesium salts.

All of the lake-mineral extraction industries have been heavily affected by the rising level of the Great Salt Lake. To combat this problem, lake industries are looking for sources of more concentrated brine and new ponding areas which are protected from the rising lake. More concentrated brine may be found deep within the density-stratified lake, or as a by-product of the West Desert Pumping Project. Areas of the western desert are also being considered for new solar-pond locations.

***Figure 38.*** *American Salt Company evaporation ponds adjacent to the Great Salt Lake (photograph credit, J.W. Gwynn).*

## METALS

Salt Lake City is located within the Oquirrh-Uintah mineral belt, a northeast-trending zone of intrusives and associated mineralization (Shaw and Stewart, 1976). Approximately 25 mining districts occur in the Utah portion of this mineral belt. Four districts are in the immediate vicinity of Salt Lake City (figure 39): Bingham (West Mountain district), Big Cottonwood, Little Cottonwood, and Hot Springs (Adams district).

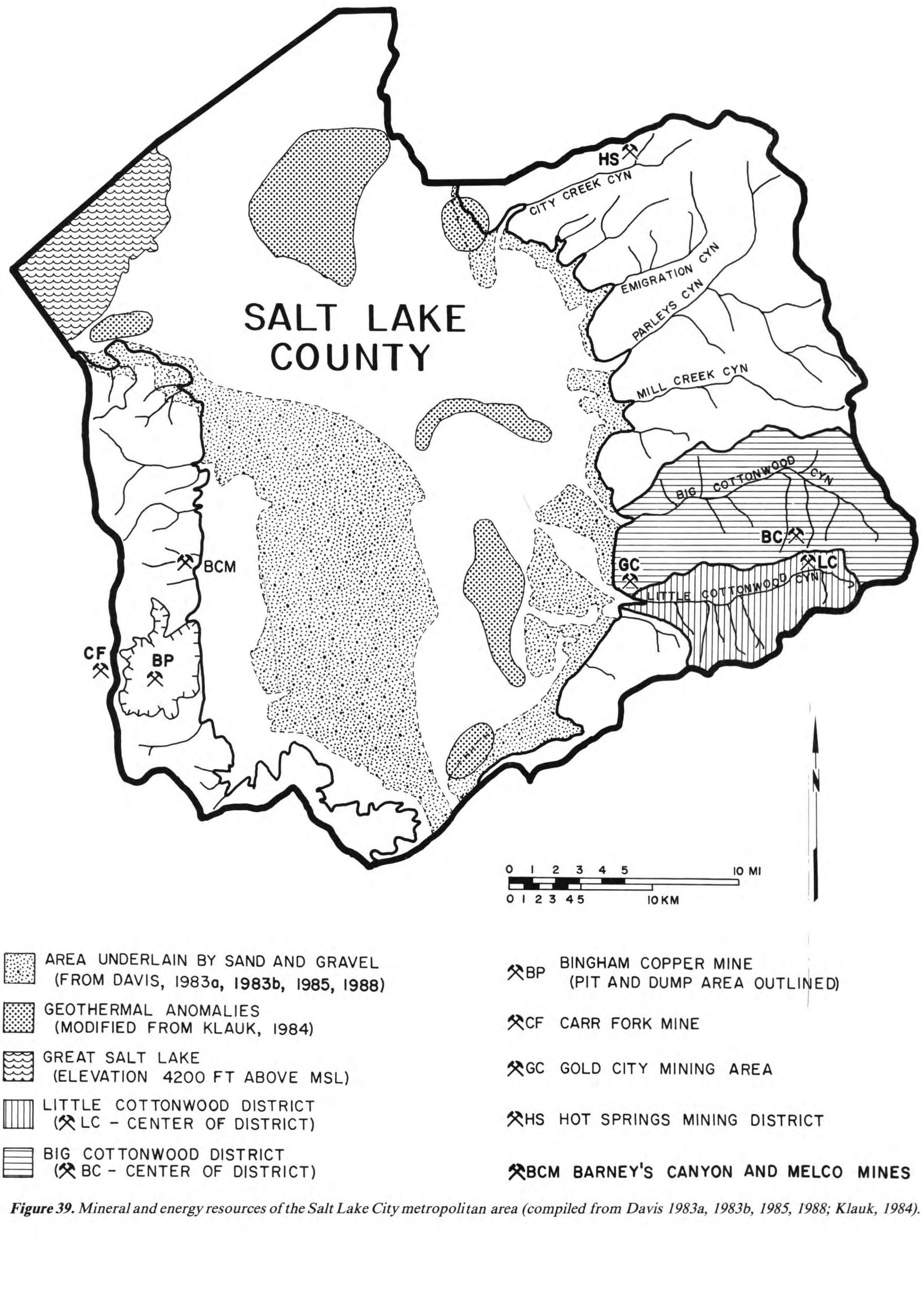



***Figure 39.*** *Mineral and energy resources of the Salt Lake City metropolitan area (compiled from Davis 1983a, 1983b, 1985, 1988; Klauk, 1984).*

## Bingham District

The Bingham district is southwest of Salt Lake City in the Oquirrh Mountains (figure 39). Mineralization was known in the area as early as 1848, but the first mining claim was not recorded until September 17, 1863 when a coalition of Mormon settlers and Union soldiers from the 3rd California Infantry located the West Jordan claim in Bingham Canyon and subsequently organized the West Mountain quartz mining district. The first profitable lode mining of lead-silver ores in the district occurred in 1865. Placer gold discovered in Bingham Canyon in 1864 was also first produced in 1865 (Hammond, 1961). Placer gold production boomed, but significant mining of the lead-silver carbonate and sulfide ores did not flourish until the completion of the transcontinental railway in 1869. In following years, placer production waned and lead-silver production increased, until 1893 when falling silver prices affected the district. The discovery of high-grade copper ores and the first commercial shipment of copper in 1896 marked the change in the district from solely lead-silver production to predominantly copper production.

The mining of low-grade, large-tonnage porphyry copper deposits was the next phase in the development of the district. A few innovative men, defying conventional mining wisdom, began porphyry mining in 1904. Both open-pit and underground methods were used until 1914, when underground copper mining was halted. The two companies involved in porphyry mining merged in 1910 (Hammond, 1961) and eventually became Kennecott Utah Copper Corporation. The Bingham open-pit mine, begun in 1906, has grown to become one of the largest man-made excavations in the world, about 2.3 miles (3.7 km) in diameter and 0.5 miles (0.8 km) deep (figure 40). By July, 1989, 5.0 billion tons (4.5 billion tonnes) of earth had been moved, yielding 13 million tons (12 million tonnes) of copper, 15 million ounces (0.47 million kg) of gold, 130 million ounces (4.0 million kg) of silver, and 853 million pounds (387 million kg) of molybdenum (Jaren Swensen, 1989). Additional by-products produced from the Bingham Mine include: lead, bismuth, platinum, selenium, rhenium, and sulfuric acid (McCarter, 1975); palladium (Kennecott, 1984b); and uranium, scandium, and tellurium (Greeley and Gloyn, 1989). As of 1964, cumulative production from the lead-zinc-silver deposits amounted to 4.18 billion pounds (1.90 billion kg) of lead, 1.71 billion pounds (0.776 billion kg) of zinc, and 136 million ounces (4.23 million kg) of silver (Rubright and Hart, 1968).

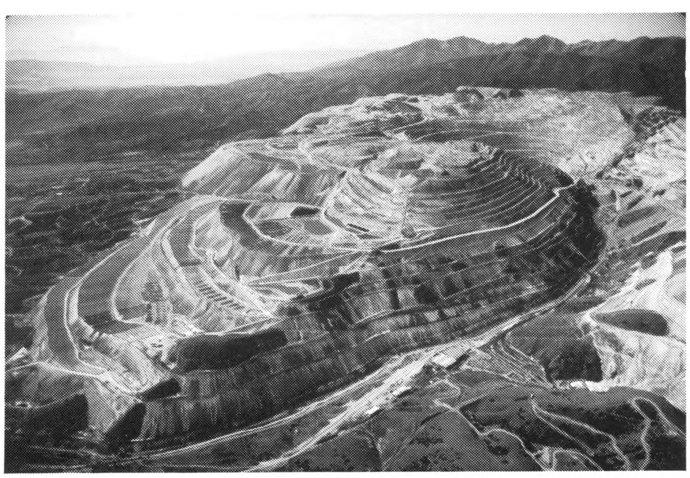


*Figure 40. Kennecott Utah Copper Corporation Bingham open-pit mine. This south-facing, low-angle aerial photograph shows the open-pit mine in the upper right corner; Bingham Canyon is in the foreground; and the mine dumps which are being leached, occupy the left center of the photograph (photograph credit, G.E. Christenson).*

Recent developments in the district include the cessation of underground lead-zinc-silver mining in 1971 (Smith, 1975), the development and subsequent shutdown of Anaconda's Carr Fork underground copper mine (and its eventual sale to Kennecott), development of Kennecott's North Ore Shoot underground copper mine, extensive renovation and modernization of the Bingham open-pit mine and ore-processing facilities, and discovery by Kennecott in 1987 of the Melco and Barney's Canyon disseminated gold deposits (figure 39). Kennecott Utah Copper Corporation has been owned successively since 1981 by Sohio, British Petroleum, and Rio Tinto Zinc.

## Big and Little Cottonwood Districts

The Big Cottonwood and Little Cottonwood mining districts are in the Wasatch Range southeast of Salt Lake City. The Big Cottonwood district covers the entire Big Cottonwood Creek drainage, but the most significant mine workings are concentrated near the head of Big Cottonwood Canyon (figure 39). The Little Cottonwood district occupies the entire Little Cottonwood Creek drainage and, like the Big Cottonwood district, has most of the significant mines at the head of the canyon (figures 39 and 41).

The first ore in the area may have been discovered in Little Cottonwood Canyon by Brigadier General Patrick Connor, commanding officer of the 3rd California Infantry (Calkins and Butler, 1943). Prospecting efforts expanded rapidly to include Big Cottonwood Canyon immediately to the north (James, 1979). On March 17, 1870, the Big and Little Cottonwood districts were organized by subdividing part of the larger, previously organized Mountain Lake district.

James (1979) provides a detailed account of the Big Cottonwood district, dividing the history into eight developmental epochs. A brief summary of his work follows. From 1871 to 1885, rapid development of the rich, oxidized, lead-silver ore took place, accompanied by the construction of local, small settlements. This boom ended in 1885 when the supply of easily accessible ore was exhausted. The period from 1885 to 1898 was characterized by a general decline of the main district. Mining operations consisted of a few hardy individuals "picking over" the mines and dumps. In 1894, the discovery of gold in the Gold City area of the district (figure 39) spawned a new exploration boom. Bull-quartz veins in the Precambrian Little Willow Formation occasionally assayed hundreds of ounces of gold per ton at the surface. However, the deposits were small and sporadically distributed, and activity in the area declined sharply by 1901, although intermittent production continued until 1946. A new period of exploration and development was sparked in the main district between 1898 and 1913 by a rise in metals prices, a new interest in copper deposits, and the local construction of smelters capable of handling complex ores. The second "boom" occurred in the district from 1914 to 1926, when deep exploration resulted in the discovery of a replacement ore

***Figure 41.*** *South Hecla Mine in the Little Cottonwood mining district, circa 1920 (photograph credit, Utah Historical Society).*

deposit along a limestone-quartzite contact on the Alta overthrust zone in the Cardiff Mine. It was the largest deposit found in the district up to that time. The period from 1926 to present has been marked by numerous, generally unsuccessful, attempts at mining.

The history of the Little Cottonwood district parallels that of the Big Cottonwood district, except that it also had a significant period of molybdenum exploration. The White Pine area of the district was the object of much molybdenum exploration during the 1940s and 1950s. The geology and molybdenum resources of this area are discussed by Buranek (1944) and Sharp (1958).

The combined production from both the Big and Little Cottonwood districts from 1867 to 1972 was 30,647 ounces (953.1 kg) of gold, 17,506,749 ounces (544,500 kg) of silver, 125,991 tons (114,298 tonnes) of lead, 6183 tons (5609 tonnes) of zinc, and 9075 tons (8233 tonnes) of copper. The aggregate value of production was $38.4 million (Bromfield and others, 1981). Small molybdenum (King, 1964), bismuth, arsenic, and antimony (Dasch, 1964) production was also reported. Tungsten also occurs in the Little Cottonwood district, but no production has been reported (Lemmon, 1964). Nackowski (1964) lists the following average assays for ore shipped from this area from 1941 to 1962; gold, 0.018 ounces/ton (0.617 g/tonne); silver, 10.14 ounces/ton (347.70 g/tonne); lead, 10.78 percent; zinc, 7.07 percent; and copper, 1.02 percent.

The future of the two districts is uncertain due to economic and environmental constraints. The occurrence of additional, small, rich silver-lead-zinc replacement deposits is probable (Calkins and Butler, 1943) and some potential exists for the occurrence of significant molybdenum deposits in the White Pine area (Bromfield and others, 1981). The negative economics of exploration and production of these small deposits make activity unlikely in the near future. Environmental considerations will also influence future production. The districts are close to a large urban population and are surrounded by the Wasatch National Forest, the Lone Peak Wilderness Area, and several ski resorts.

## Hot Springs District

The Hot Springs district, which incorporated the older Adams district, is a few miles northeast of Salt Lake City at the head of City Creek Canyon (figure 39). Mining activity in this minor district is poorly recorded in the literature. Scant information is presented in Huntley (1885), Butler and others (1920), and a few articles in the *Salt Lake Mining Review,* an old mining newsletter. The ore deposits of the district were small, low-grade veins in Middle Cambrian to Mississippian carbonates. Mineralization consisted chiefly of argentiferous galena and cerussite in ocherous gangue. Gold, copper, and zinc were present in minor quantities. The last recorded production from the district in 1910 was valued at $50/ton ($55/tonne).

## INDUSTRIAL ROCKS AND MINERALS

Industrial rocks and minerals were some of the first commodities produced after arrival of the Mormon pioneers in 1847. The recent trend in the production of nonmetallics is toward construction materials and away from heavy-industry-related products such as deadburned dolomite for the steel industry. Important industrial rocks and minerals in the Salt Lake City metropolitan area include cement, construction aggregate, crushed stone, industrial sand, clay, dimension stone, and sulfur and sulfuric acid.

### Cement

Portland Cement Company of Utah (a division of Lone Star Industries, Inc.) operates a 400,000-ton (363,000-tonne) per year, wet-process plant in downtown Salt Lake City. The plant utilizes materials imported primarily from outside the Salt Lake Valley. Cement raw materials include high-calcium limestone which is combined with shale, gypsum, and steel-mill scale from a local steel plant. The market value of portland cement in Utah in 1986 was approximately $58/ton ($64/tonne) (Burgin, 1987).

### Construction Aggregate

The Salt Lake City area has abundant sand and gravel deposits, predominantly in Lake Bonneville sediments. Lake Bonneville elevation oscillations, combined with delta-building at canyon mouths and longshore currents from prevailing winds, deposited high-quality sand and gravel in many parts of the Salt Lake Valley (figure 39). The sand and gravel resources in the Salt Lake City metropolitan area are still sizable, but encroaching urbanization has made much of the resource inaccessible. Deposits presently being worked are, in many cases, nearing depletion, and mining operations are unable to expand due to surrounding development. This problem was anticipated nearly 20 years ago when Davis and Meyer (1971) predicted that only a 20-year supply of high-quality accessible reserves remained. One indication of this depletion is the recent initiation of crushing of carbonate rock for aggregate at a depleted local gravel pit. Conflict between property owners and pit operators accompanies this land-use confrontation. Complaints have been made about dust, noise, truck traffic, and visual-degradation problems accompanying the sand and gravel operations. In one case, a pit operator faced public displeasure because his operation allegedly disturbed air currents at a nearby hang-gliding locality (Burgin, 1984).

Production of construction sand and gravel in Utah for 1986 amounted to 15.9 million tons (14.4 million tonnes) and was worth $36.9 million (Burgin, 1987). Most of this material was produced and consumed in the Salt Lake City metropolitan area.

### Crushed Stone and Industrial Sand

Crushed stone for use in aggregate and other engineering applications is currently produced by two companies. Monroc, Inc. crushes Paleozoic carbonates at its Beck's Spur location and Rocky Mountain Energy crushes copper smelter slag for railroad ballast (Tripp, 1985). Utah's production of crushed stone in 1986 was 4.5 million tons (4.1 million tonnes) and had a value of $14.1 million (Burgin, 1987). A sizable fraction of the stone was used in the Salt Lake City metropolitan area. Three producers of industrial sands are known in the Salt Lake City metropolitan area. Salt Lake Valley Sand and Gravel processes Lake Bonneville sediments into sand-blasting and metal casting sand. Rocky Mountain Energy and Blackhawk Slag Products produce sand-blasting sand from smelter slag.

### Clay

Salt Lake City is the center of the clay-products industry in Utah. The largest local producer of clay products, Interstate Brick, maintains a large, modern facility which produces brick and tile from clays blended from numerous quarries around the state (Tripp, 1985). Argillite from the Precambrian Big Cottonwood Formation was mined locally for use in clay products (Van Sant, 1964; Crawford and Tuttle, 1964), but encroaching housing developments forced the closure of the quarry. Previous production in the Salt Lake Valley of detrital clay, pedogenic clay in Lake Bonneville sediments, and pre-Lake Bonneville, water-lain, altered volcanic ash is reported by Crawford and Tuttle (1964).

### Dimension Stone

While no dimension stone currently is produced in the Salt Lake City metropolitan area, it has been an important commodity historically. Little Cottonwood stock quartz monzonite was quarried (figure 42) for many prominent Salt Lake City buildings including the Salt Lake City LDS Temple and the Utah State Capitol Building. The Triassic-Jurassic Nugget Sandstone (Navajo Sandstone

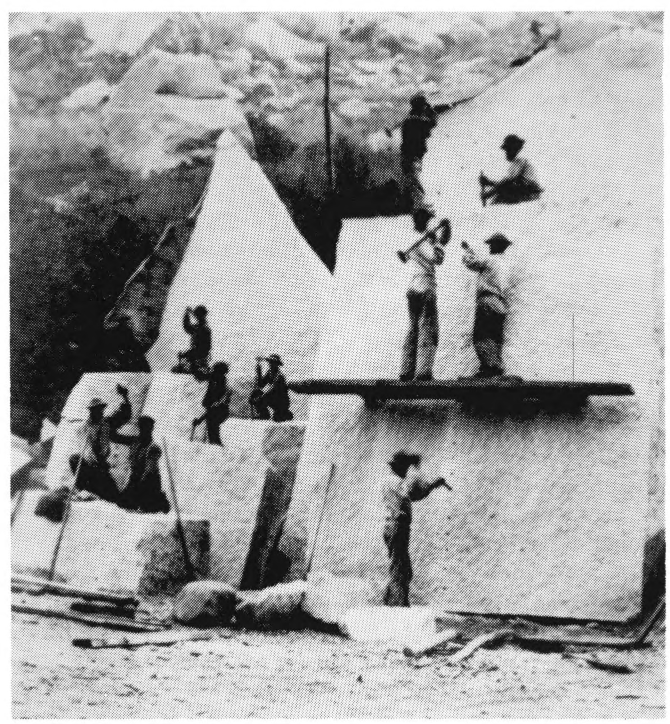


***Figure 42.*** *Quarrying granite (Little Cottonwood stock quartz monzonite) in Little Cottonwood Canyon for the LDS Salt Lake City Temple, circa 1870 (photograph credit, Utah Historical Society)*

equivalent), a medium-grained, somewhat friable, tan-to-red sandstone was used by the U.S. Army for the construciton of Fort Douglas beginning in 1874, and in the foundations and walls of many private residences.

### Sulfur and Sulfuric Acid

Sulfur is produced in small quantities in the Salt Lake Valley as a by-product of oil refining at the Chevron USA Inc. Salt Lake Refinery. Sulfuric acid is produced in large quantities by Kennecott Utah Copper Corporation as a by-product of copper smelting. The sulfuric acid was long utilized in the acidulation of phosphate rock to produce fertilizer at Chevron's Garfield fertilizer plant. However, this plant has been closed and the fertilizer operation was transferred to Rock Springs, Wyoming in 1986.

## ENERGY RESOURCES

### Geothermal

Six areas within Salt Lake City metropolitan area (figure 39) contain three or more low-temperature geothermal wells or springs. The waters within these areas fall within the 68 to 302°F (20 to 150°C) temperature range. Within the Warm Springs fault and Crystal Hot Springs areas, waters issue from springs and range in temperature from 90 to 185°F (32 to 85°C). In the other four areas, water encountered in wells ranges from 68 to 118°F (20 to 48°C). Several of the geothermal occurrences are fault-related and have been used for recreational purposes in the past. The water from Crystal Hot Springs currently is utilized to heat greenhouses, where roses are grown year round, and to heat the minimum-security facility at the Utah State Prison.

### Oil and Gas

The Salt Lake City area has seen intermittent oil and gas exploration since the late 1920s. Most test wells have been relatively shallow, less than 4500 feet (1372 m), intended to evaluate Pleistocene and Tertiary lacustrine sediments. No significant quantities of hydrocarbons have been found; however, exploration by Amoco Production Company between 1978 and 1981 beneath the Great Salt Lake did delimit a potential oil reserve. Fifteen wells were drilled from a barge on the lake. Most of the wells encountered only oil and gas shows, but one well recovered a low gravity, high sulfur oil. The apparent structural trap is a faulted anticline with 300 feet (91 m) of vertical closure. The reservoir is thought to be the Pleistocene West Rozel Basalt (Bortz and others, 1985).

Campbell (1985) assessed the petroleum potential for the central Wasatch Front by dividing the area into five geological terrain types and then ranking them according to their petroleum potential. The Salt Lake City metropolitan area lies in what Campbell (1985) termed shallow Great Salt Lake Cenozoic basin terrain. He considered the petroleum potential of that area to be low. However, small gas reserves probably exist within the shallow Pleistocene strata found in the area. In addition, there may be potential targets at greater depths in Mesozoic and Paleozoic formations, but little exploration has been done in the deeper part of the basin.

## MINERAL REGULATIONS AND ZONING

Mineral production in the Salt Lake City metropolitan area is regulated by city, county, state, and federal governments. The regulating agencies and their areas of concern are briefly summarized below.

The Salt Lake City Division of Planning and Zoning operates in conjunction with the Salt Lake City Planning Commission to regulate any mining-related excavation activity within the Salt Lake City limits. Proposed mineral development must first meet zoning requirements. Site-development regulations, which govern the actual excavation at the site, must then be followed. A geotechnical report on the proposed excavation must be filed with the city.

The Salt Lake County Planning and Zoning Department has regulations affecting mineral development on private land within the Salt Lake County boundaries, but not within the incorporated area of Salt Lake City. Essentially, proposed mineral development can only take place on land zoned for that activity.

The Utah Department of Natural Resources, Division of Oil, Gas, and Mining (DOGM) has regulations affecting mineral operations other than sand and gravel mining on all federal, state, and private land in Utah. A mining plan with reclamation provisions and a reclamation bond are required from all mineral operators who anticipate disturbing more than 5 acres (2 ha) of land.

The Utah Department of Health, Division of Environmental Health consists of four bureaus: Air Quality, Solid and Hazardous Waste, Radiation Control and Uranium Mill Tailings, and Drinking Water and Sanitation. Each bureau has its own regulations that apply to all federal, state, and private land. However, many types of mining activities are exempt from regulation by this agency due to jurisdictional overlap with other regulatory agencies. A prospective mineral producer would typically arrange for a predesign conference to determine the applicable regulations of the four separate bureaus.

The U.S. Bureau of Land Management and the U.S. Forest Service are responsible for regulating mining activity on Federal land under their jurisdiction. The agencies handle the claim, lease, and sale of minerals and set stipulations on how mineral extraction is done and generally cooperate on environmental regulation with the DOGM.

## THE GREAT SALT LAKE: A HAZARDOUS NEIGHBOR

*Genevieve Atwood, Don R. Mabey, William R. Lund*

At the historic low level of the Great Salt Lake in 1963, about 10 miles$^2$ (26 km$^2$) of land in the northwest corner of the Salt Lake Valley were covered by lake water. At the historic high levels in the 1870s and again in the 1980s about 90 miles$^2$ (233 km$^2$) of land were covered. In addition to the problem of periodic flooding associated with fluctuations of the lake level, flooding may also occur due to both local and distant earthquakes and wind tides. Engineered structures founded on the lake bed, particularly those designed to provide protection from the lake water, pose special engineering-geology problems.

### LAKE HISTORY

Over the past several million years, lakes have been common features in northwestern Utah. The geologic records of the two most recent lakes, late Pleistocene Lake Bonneville and Holocene Great Salt Lake have been investigated in considerable detail, and a chronology of the two lakes is emerging from studies of lake features and sediment cores. For the last 11,000 years, fluctuations of the Great Salt Lake have been relatively small, ranging from low levels when the lake nearly vanished to high levels not exceeding 4221 feet (1287 m) in elevation. Lake fluctuations respond to minor changes in climate and are greatly influenced by the topography of the basin, which controls the ratio of surface area to volume. This ratio changes dramatically as the lake rises from 4215 to 4217 feet (1285 to 1285 m) and extends into the Great Salt Lake Desert, greatly expanding its surface area and tending to stabilize its elevation (figure 43).

The rise and fall of the lake is highly sensitive to relatively minor variations in precipitation, stream inflow, and evaporation. The Great Salt Lake receives water from three sources: direct precipitation, stream inflow, and ground-water discharge. Due to the extremely flat bottom of the lake and correspondingly large increase in surface area as the lake level increases, less water is required to raise the lake elevation when the lake level is low than when the lake level is high. Until the recent completion of the West Desert Pumping Project, the only loss of water from the lake was by evaporation, which is controlled by climate. Cool, cloudy summers greatly reduce evaporation from the lake. Human activity on and around the lake also has a significant impact on the lake level. Consumptive use of water from rivers and streams flowing to the Great Salt Lake diverts water that would otherwise cause the level of the lake to rise, while diking and pond construction on the lake bed may raise or lower the elevation of parts of the lake. Before it was breached in 1984, the Southern Pacific Railroad causeway caused the main body (south part) of the lake to be about 3 feet (0.9 m) higher and substantially less saline than it would have been if the causeway had not restricted water movement. Intermittent pump-

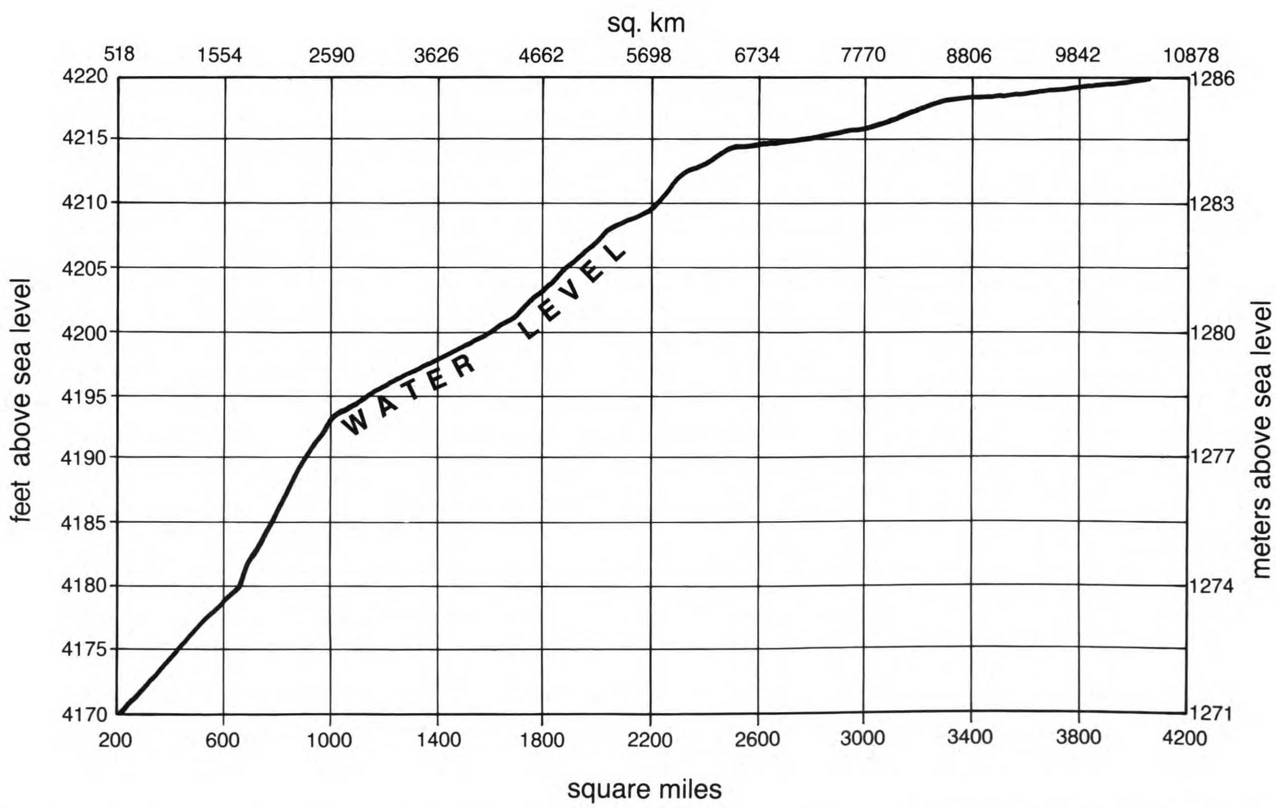



***Figure 43.*** *Area-elevation curve for the Great Salt Lake. Note the abrupt increase in area with increasing elevation beginning about 4212 ft (1284 m).*

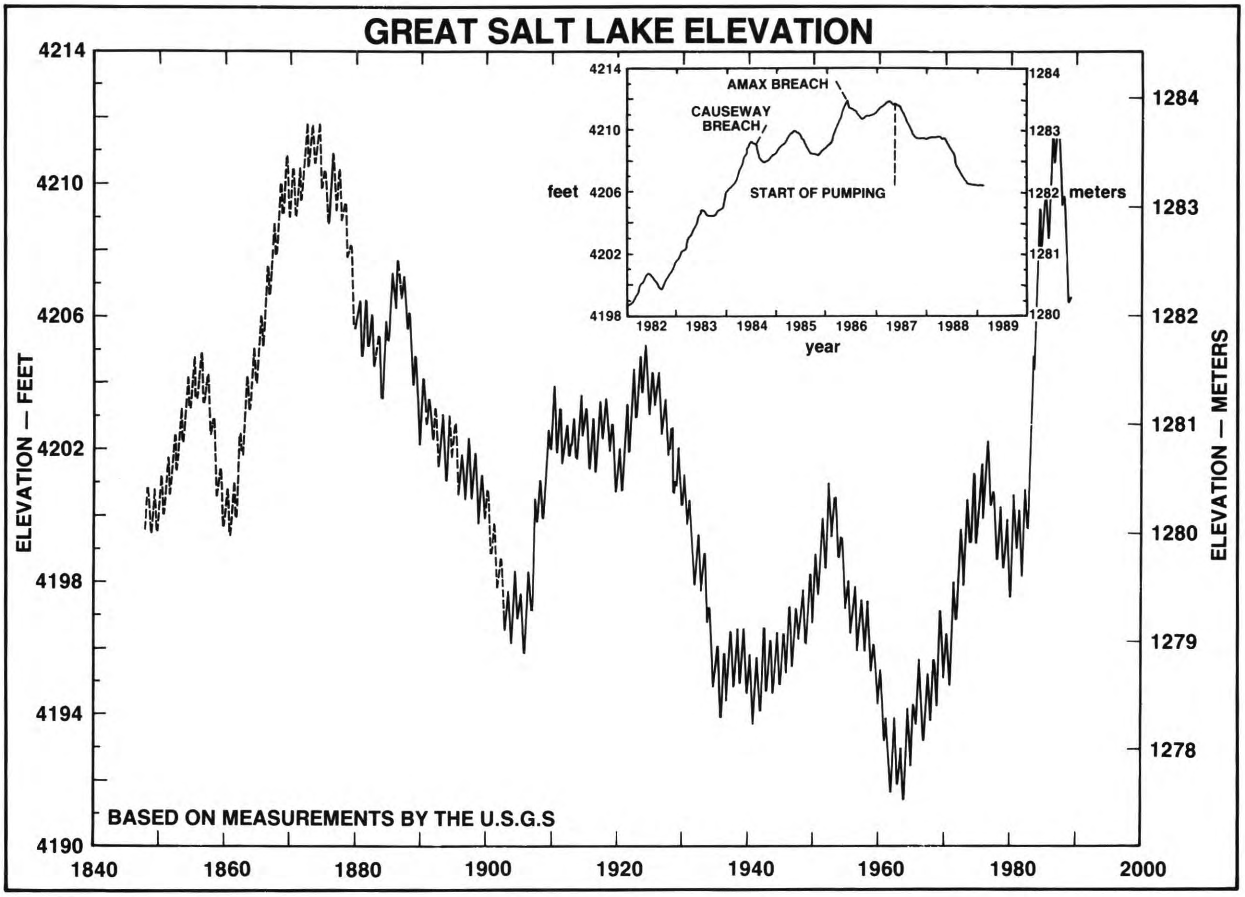



***Figure 44.*** *Hydrograph of the Great Salt Lake. Elevations before 1875 are inferred from traditional accounts.*

ing of water into the Great Salt Lake Desert since 1986 has contributed to a lowering of the lake.

Historical data on the lake extends from the 1840s. For the time before 1875, when the first lake gauge was established (figure 44), lake-level data are based on the recollections of several observers of water conditions on the bars connecting Antelope and Stansbury Islands to the mainland and the measured elevation of the highest stormline formed in the 1870s. Measurements of the lake level after 1875 record the fluctuations of the lake, although these measurements, particularly early records, may vary considerably in their accuracy. Evidence for lake-level fluctuations prior to the 1840s is geomorphic, from shorelines (Currey and Oviatt, 1985); geochemical, from lake sediments (McKenzie and Eberli, 1985); paleontological (Forester, 1986); and archeological (Currey and James, 1982).

## FLOOD HAZARD

Unlike more catastrophic events such as large earthquakes or stream flooding, which happen suddenly with little or no warning, changes in the level of the Great Salt Lake are relatively slow, and the potential for flooding depends on the level of the lake at the time the rise begins. Although there is much still to be learned about fluctuations of the lake, work done in the last few years has defined the approximate recurrence interval of some of the lake-level changes.

### Daily Fluctuations

No significant diurnal tides occur on the Great Salt Lake, but wind seiches are common. The largest wind seiches develop on the main body of the lake in response to winds from the south or west. Lin and Wang (1978) reported that wind velocities in excess of 10 knots (18.5 km/hr) for at least 12 hours are required to create a major wind seiche. In response to a south wind, the water level declines in the south-shore area and increases to the north along the Southern Pacific Railroad causeway which divides the lake approximately in half. When the wind velocity declines to less than 10 knots (18.5 km/hr), the water levels in the south and north ends of the lake begin to equilibrate and the seiching phase begins (figure 45). The fundamental period of the wind-induced waves is approximately 6 hours and the seiching lasts about 2 days. As much as 2 feet (0.6 m) of flooding can be expected at the south shore as a result of seiching. The seiches are strongly dependent on lake characteristics, including surface area, depth, and bottom configuration. Thus, as the level of the lake fluctuates, or when engineered structures restrict water movement, the seiching characteristics change. When the Southern Pacific Railroad causeway was constructed, the fundamental period of seiching in the main body of the lake changed from 9 hours to 6 hours.

The effect of wind-generated waves can be quite severe along the shore of the Great Salt Lake. The combined set-up and run-up of wind-generated waves, which can exceed 7 feet (2 m), depends on the slope of the lake bed and the exposure of the shore with respect to the incoming waves. Because wave energy is proportional to fluid density, when the salinity of the lake is high (lake level is low), the energy for waves of a given amplitude is considerably greater than for fresher water.

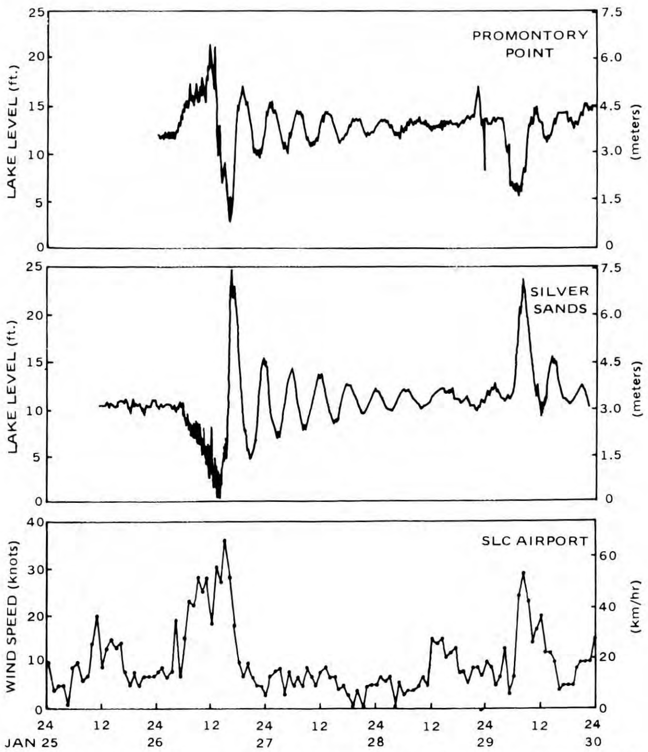



*Figure 45. Great Salt Lake seiche hydrographs for Promontory Point and Silver Sands (south shore) and wind speed at the Salt Lake City International Airport showing wind seiches over a 5-day period of 1.0 feet (0.3 m) with a maximum amplitude of 1.5 feet (0.6 m) and a duration of 48 hours (from Lin and Wang, 1978).*

## Seasonal Fluctuations

The level of the lake goes through a seasonal cycle, peaking in spring or early summer in response to spring runoff and reaching a low in the fall at the end of the period of high evaporation. The maximum measured seasonal lake rise was 5 feet (1.5 m) in 1983; some seasonal rises have been less than 1 foot (0.3 m). The maximum measured seasonal lake decline was 3.0 feet (0.9 m) in 1988. The seasonal variations in lake level are controlled largely by the weather and cannot be predicted accurately. The size of these variations is partly dependent on the level of the lake. The seasonal rise of the lake occurs at a maximum rate of about 1 inch/day (2.5 cm/day) and thus does not present a direct threat to life.

## Recurring Inundation

In the 140 years of historical record, the Great Salt Lake has reached the 4211+ feet (1284+ m) elevation twice, once in the 1870s and again in the 1980s. Work by Currey (1987) has documented lake levels since the drop of Lake Bonneville from the Provo level 13,000 yr BP. Studies of shorelines, lake deposits, and river sediments associated with various lake levels indicate that 4221 ft (1287 m) is the highest elevation attained by the lake since the Gilbert level 11,000 yr BP. Based on geochemical and geomorphic evidence, it appears that this level was reached once, and perhaps twice, in the last 10,000 years and that the high level occurred in response to climatic conditions that were cooler and wetter than today's. Thus, a preliminary recurrence interval for the rise of the lake to the 4221 feet (1287 m) elevation appears to be on the order of 5000 years and such a rise may require a significant change in climate. McKenzie and Eberli's (1985) isotope-chemistry work allows for up to five freshenings of the lake waters, indicating lake levels at least as high as 4212 feet (1284 m) in the last 600 years. Geomorphic evidence (shorelines) constrains these lake high stands as below 4221 feet (1287 m) and most likely between 4212 and 4217 feet (1284 and 1285 m) in elevation (Currey, 1987). The likelihood that the Great Salt Lake will rise again to the elevation of 4221 feet (1287 m) during the useful life of structures constructed today is remote, and the possibility of floods at that level can be reasonably ignored. However, archeological evidence indicates a relatively recent (last 300-400 years) inundation to an elevation of 4217 feet (1285 m) (Currey and James, 1982).

Both historical and geological data show that the normal fluctuations of the Great Salt Lake include periodic rises to elevations between 4211 and 4217 feet (1284 and 1285 m) at intervals of about 100 years or so. Therefore, for planning purposes, construction of a permanent facility at an elevation below 4217 feet (1285 m) should assume a reasonable possibility of flooding during the structure's lifetime. Weber County, north of Salt Lake City, adopted a planning resolution following the rise of the Great Salt lake in 1983 that sets a moratorium on building below the 4215 feet (1285 m) elevation and reviews each building application on a case-by-case basis below the 4218 feet (1286 m) elevation (Lowe, 1987). Governmental entities bordering the lake in the Salt Lake City metropolitan area have not adopted such ordinances.

Actual and potential costs to Salt Lake County for flooding at elevations of 4212 feet (1284 m), 4214 feet (1284.5 m), and 4216 feet (1285 m) are summarized in table 9. These figures do not include costs associated with lost tourism, lost commercial trade, or increased costs for public services. If the lake rises from 4212 feet to 4217 feet (1284 to 1285 m), potential additional costs to Utah may exceed $3 billion (Steffan, 1986). If the lake rose to the 4217 feet (1285 m) elevation, and no action was taken to prevent flooding, northern Salt Lake City would suffer great financial loss due to flooding of residential and business areas and transportation corridors; Morton Salt Company's continued operation would be doubtful; Salt Lake City's International Airport would be affected; the sections of Interstate Highway 80 along the south shore of the lake would be flooded. At this level, raising the Interstate would be incompatible with existing highway overpasses. Wastewater-treatment plants near the lake would require diking to prevent flooding, and numerous septic-tank systems that drain to lower areas near

**TABLE 9.**

*Actual (for 4212 feet; 1284 m) and potential (for 4214 feet and 4216 feet; 1284.5 m and 1285 m) damages and capital investments for Salt Lake County resulting from a rise in the elevation of Great Salt Lake (adapted from Steffen, 1986).*

| Lake Elevation | Mineral Industry | Other Industry | Residences | Roads and Highways | Public Utilities/ Public Facilities | Agriculture (Cumulative Damage) |
|---|---|---|---|---|---|---|
| 4212 feet (1284 m) | Repairs required to Morton Salt dikes. | Industrial area north of Rose Park and west of I-15 is as low as 4206 feet (1282 m). Some businesses implemented flood-control measures (diking, pumping, raising parking lots/ driveways). | Diking/pumping of Jordan River, City Drain, and Oil Drain to be implemented — $2 million. | I-80 dike east of Black Rock to be repaired and raised. Diking to be constructed along I-80 near 90th West. Costs of these projects $2 to $3 million. | SLC wastewater-treatment plant required to pump effluent into Oil Drain. SLC Airport required to pump runway drains. | $4.2 million |
| 4214 feet (1284.5 m) | Morton Salt is uncertain whether it would raise its dikes. The cost would be $1-1.5 million | | Dikes along Jordan River, City Drain, and Oil Drain would need to be raised and extended and additional pump stations installed. | Lowest portions of I-80 are at 4213 feet (1284 m). I-80 west of 5600 West would close — traffic diverted to 2100 South Redwood Road would require protection. | | $4.2 million |
| 4216 feet (1285 m) | Morton Salt continued operations doubtful. | | | Redwood Road would have to be raised. | North and West perimeters of the airport would have to be diked. | $6.5 million |

the lake would be non-operational. Because of the low slope gradients near the Great Salt Lake, the impact on drainage systems would extend well beyond the areas of actual flooding. Additional impacts would include the loss of business revenues, household income losses, and tax-revenue reductions.

## FLOOD MITIGATION

Between September 1982 and April 1986, in response to much above normal precipitation in northern Utah, the level of the Great Salt Lake rose from 4200 feet (1280 m) to 4211.85 feet (1285 m) equaling its previous historical high in the 1870s. The rapid lake-level rise doubled the volume of the lake and increased its surface area by nearly 500,000 acres (202,350 ha). The associated flooding caused more than $240 million damage to facilities within and adjacent to the lake (Austin, 1988). As a flood control measure, the Southern Pacific Railroad causeway, which divided the lake into two areas of unequal surface elevation, was breached in August 1984. The breach reduced the level of the higher, southern main body of the lake by about 0.7 feet (0.2 m) and increased the level of the lower northwest part of the lake by about twice that amount. However, relief from flooding around the more developed main body of the lake was short-lived, as the lake continued to rise, reaching its record high two years later. Local diking and pumping were required to protect critical facilities and residential areas around the lake.

In response to the flooding, the Utah State Legislature authorized a study by the Utah Division of Water Resources (1984) of lake flood-control measures that included upstream storage and diversion, diking, and pumping. The Legislature specified that the method selected be cost effective, capable of quick implementation, and repeatable on an annual basis if wet conditions continued or reoccurred in the future. As the proposed flood-control methods were evaluated, it became evident that only pumping the excess lake water into the shallow desert basin west of the Great Salt Lake, where accelerated evaporation could occur, could be implemented quickly enough to halt the current flooding cycle. Construction began in 1986 on a 10-mile-long (16 km) access road, a pumping station, a canal, trestles, dikes, a 37-mile-long (59.6 km) natural-gas pipeline, and a 500 mile$^2$ (1295 km$^2$) evaporation pond. Pumping began in mid-1987, and by the end of 1988 about 2.05 million acre-feet (2.52 billion m$^3$) of brine had been pumped from the Great Salt Lake (Palmer, 1989). The lake level had dropped 5.4 feet (1.6 m) by December 1988 due to a combination of pumping, evaporation, and decreased inflow resulting from two dryer than average years.

Several other diking and pumping schemes have been proposed for the Great Salt Lake either to prevent flooding or, more recently, to provide fresh water storage in part of the lake basin. Some of the proposed dikes would be tens of miles (km) long and tens of feet (m) high. The geology of the bed of the Great Salt Lake varies substantially, and detailed studies would be required to determine the engineering properties of the lake bottom along dike alignments. Such studies are particularly important if the dikes are to protect populated areas. The impounding of water behind a dike, accompanied by development in areas that would otherwise be flooded, has the potential to change a property-threatening hazard into a life-threatening hazard in the event of a dike failure. Ground shaking during earthquakes may vary substantially across the lake bed. Dikes intended to protect populated areas should be designed to withstand ground shaking from the largest anticipated earthquake. Furthermore, following an earthquake, tectonic deformation combined with seiching could cause the lake to overtop dikes and result in flooding and the trapping of a substantial amount of water on the populated side of proposed dikes.

## OTHER LAKE—RELATED GEOLOGIC HAZARDS

In addition to inundation and wave damage, construction in or near the lake must consider the hazards related to earthquakes, liquefaction, problem-soil conditions, high ground water, and poor drainage discussed in earlier sections of this paper. Rafting ice is another, often overlooked, hazard associated with construction in the lake. Ice forming on the lake's surface, together with additional precipitation falling on the frozen lake, creates ice wedges that can, when driven by storm winds, shear off or topple structures, such as transmission-line poles and drilling platforms. Formation of ice increases when the lake level is high and salinity is reduced.

There appear to be few engineering problems associated with a reduction in the level of the lake. However, dike and causeway embankment failures may result as lake levels drop, and the buoyancy forces that partially supported the fill material are reduced. During dry periods when the lake is at a low level, episodes of blowing dust and salt are common.

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