Studies of Geology and Hydrology in the Basin and Range Province, Southwestern United States, For Isolation of High-Level Radioactive Waste— Characterization of the Bonneville Region, Utah and Nevada

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1370-G

Prepared in cooperation with the States of Arizona, California, Idaho, Nevada, New Mexico, Texas, and Utah

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Looking north of Blue Lake Springs at the southwestern margin of the Great Salt Lake Desert, Tooele County, Utah. Springs at and near Blue Lake Springs discharge 23.44 cubic hectometers of water per year. Carbonate rocks of Paleozoic age are exposed immediately to the left of the photograph. Photograph by K.A. Sargent (1984).

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Edited by M.S. BEDINGER, K.A. SARGENT, *and* WILLIAM H. LANGER

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For readers who wish to convert measurements from the metric system of units to the inch-pound system of units, the conversion factors are listed below.

Multiply SI unit	*By*	*To obtain U.S. customary unit*
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic hectometer (hm^3)	810.7	acre-foot (acre-ft)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
liter (L)	0.2642	gallon (gal)
	Mass	
megagram (Mg) or metric ton	1.102	short ton (2,000 lb)
	Temperature	
degree Celsius (°C)	9/5 (°C) + 32 = °F	degree Fahrenheit (°F)
	Chemical Concentrations	
milligram per liter (mg/L)	About 1	part per million

STUDIES OF GEOLOGY AND HYDROLOGY IN THE BASIN AND RANGE PROVINCE, SOUTHWESTERN UNITED STATES, FOR ISOLATION OF HIGH-LEVEL RADIOACTIVE WASTE— CHARACTERIZATION OF THE BONNEVILLE REGION, UTAH AND NEVADA

Edited by M.S. BEDINGER, K.A. SARGENT, and WILLIAM H. LANGER

ABSTRACT

The Bonneville region of the Basin and Range province in west-central Utah and adjacent Nevada includes several basins lying south of the Great Salt Lake Desert. Physiographically, the region consists of linear, north-trending mountain ranges separated by valleys, many of which are closed basins underlain by thick sequences of fill. Surface drainage of open basins and ground-water flow is to the Great Salt Lake Desert. In structure and composition the ranges are faulted Paleozoic rocks, locally intruded by Mesozoic and Tertiary plugs and stocks. In the southern and northeastern parts of the region, volcanic rocks are widespread and form large parts of some mountain ranges. The Paleozoic sedimentary rocks include great thicknesses of carbonate rocks which compose a significant aquifer in the region.

Media considered to have potential for isolation of high-level radioactive waste in the region include intrusive rocks, such as granite; ash-flow tuff; and basalt and basaltic andesite lava flows. These rock types, basin fill, and possibly other rock types, may have potential as host media in the unsaturated zone. Quaternary tectonism in the region is evidenced by seismic activity, local areas of above-normal geothermal heat flow, Quaternary faulting, late Cenozoic volcanic activity, and active vertical crustal movement.

The Bonneville region is part of a large ground-water flow system that is integrated partly through basin-fill deposits, but largely through an underlying carbonate-rock sequence. The region includes: (1) several topographically closed basins with virtually no local surface discharge that are drained by the underlying carbonate-rock aquifer; (2) closed basins with local surface discharge by evapotranspiration; and (3) basins open to the Great Salt Lake Desert that discharge by ground-water underflow and evapotranspiration. The carbonate-rock aquifer discharges to large springs in the Desert and in basins tributary to the Desert. The climate is arid to semiarid with the greatest precipitation in the mountain ranges. Most recharge probably occurs by infiltration of runoff as it leaves the mountains, although some recharge probably occurs directly to the carbonate rocks in the mountain areas. The concentration of dissolved solids in ground water is generally less than 500 milligrams per liter. Dissolved-solids concentrations increase in the Great Salt Lake Desert and in major valleys adjoining the Desert. The predominant chemical constituents in ground water are calcium, magnesium, and sodium bicarbonate. Chloride-type water is associated with the higher dissolved-solids content of water in and near the Great Salt Lake Desert.

The majority of the mineral occurrences containing base- and precious-metal deposits in the Bonneville region are of Tertiary age. Fluorspar is the primary industrial mineral. Coal, oil, and gas have not been produced in significant amounts.

Manuscript approved for publication, February 26, 1985.

INTRODUCTION

By M.S. Bedinger and K.A. Sargent

BACKGROUND AND PURPOSE

A study by the U.S. Geological Survey to evaluate potential hydrogeologic environments for isolation of high-level radioactive waste in the Basin and Range physiographic province of the southwestern United States was begun in May 1981, with the introduction of the study to the Governors of eight Basin and Range States—Arizona, California, Idaho, Nevada, New Mexico, Oregon, Texas, and Utah—and to respective Indian tribes in those States. Accordingly, these States were invited to participate in the study by designating an earth scientist to serve on a Province Working Group with the U.S. Geological Survey—membership of the working group is shown following the title page. State representatives have provided consultation in selecting guidelines, assembling geologic and hydrologic data, and assessing such information to identify environments that meet the guidelines for further study.

The guidelines for evaluation of the regions and the rationale for their study as well as the basis for hydrogeologic characterization of the regions are given in Chapter A of Professional Paper 1370 (Bedinger, Sargent, Langer, and others, 1989). The evaluation of the regions is given in Chapter H (Bedinger, Sargent, and Langer, in press). The titles of chapters in this series are as follows:

A Basis of characterization and evaluation
B Characterization of the Trans-Pecos region, Texas
C Characterization of the Rio Grande region, New Mexico and Texas
D Characterization of the Sonoran region, Arizona
E Characterization of the Sonoran region, California
F Characterization of the Death Valley region, Nevada and California
G Characterization of the Bonneville region, Utah and Nevada
H Evaluation of the regions

These chapters are integrated and contain a minimum of repetition. The reader needs to consult Chapters A and H and the appropriate regional Chapters B through G in order to achieve a complete understanding of the characterization and evaluation of an individual region.

Additional background information on this study is given in reports on the province phase of characterization and evaluation by Bedinger, Sargent, and Reed (1984); Sargent and Bedinger (1985); and Bedinger, Sargent, and Brady (1985).

This report, Characterization of the Bonneville region, Utah and Nevada, Chapter G, is one of six reports characterizing the geology and hydrology of the regions of study in the Basin and Range province. Chapter G is divided into six separately authored sections: (1) Introduction, (2) Geology, (3) Potential host media for radioactive waste, (4) Quaternary tectonism, (5) Groundwater hydrology, and (6) Mineral and energy resources. Although the report was prepared under the general guidelines set by the Province Working Group, the scope of individual sections was established by their respective authors.

This chapter provides the geologic and hydrologic framework necessary to evaluate the Bonneville region for relative potential for isolation of high-level radioactive waste. Because of the limited and specific goals of the project, emphasis is placed on the characteristics of the region that relate to waste isolation.

The results of this study are not based on original data; no new field work was conducted specifically for this project. It is not intended to be a definitive report on the geologic and hydrologic aspects of the region, but it provides a general summary of published and unpublished data that are available.

GEOGRAPHIC SETTING

The Bonneville region is in the northeastern part of the Basin and Range province and covers most of west-central Utah and a thin strip of adjacent Nevada (pl. 1). The region physiographically consists of linear, north-trending mountain ranges separated by valleys, many of which are closed basins. The relief between the valleys and adjoining mountains is generally 1,000–1,500 m, but locally may be as much as 1,800 m. Figure 1 shows the western face of the House Range with a relief of 1,230 m above Tule valley. The view northward from the House Range to Fish Springs Range is shown in figure 2. The Great Salt Lake Desert forms the lowest basin at about 1,300 m above sea level, and no basin flats exceed 1,800 m in elevation. Mountains cover about a third of the region and reach their maximum elevation at Wheeler Peak (3,982 m) in the Snake Range of Nevada. Piedmont-gravel fans cover areas between ranges and basins. Fans are more extensive in the Bonneville region than in higher parts of the Basin and Range province.

In structure and composition the ranges are mostly complexly faulted Paleozoic rocks locally intruded by Mesozoic and Tertiary plugs and stocks. In the southern and northeastern parts of the region, volcanic rocks

FIGURE 1.—View from Tule Valley of the western face of the House Range showing interbedded thick Cambrian carbonate rocks and thin shales overlying the Prospect Mountain Quartzite. In descending order, the stratigraphic units are: Swasey Limestone (topmost knobs), Whirlwind Formation (shaley limestone bench), Dome Limestone (cliff former), Chisholm Shale (bench), Howell Limestone (cliff former), Tatow Member of the Pioche Shale (silty carbonate rocks), Pioche Shale (lower part), Prospect Mountain Quartzite, and basin fill. Tatow Knob, the highest point (A) in the photograph (2,602 meters), is 1,230 meters above the valley floor. Photograph by C.D. Walcott (1903).

are widespread and compose large areas of some mountain ranges.

ACKNOWLEDGMENTS

This report and the other reports in this series were prepared in cooperation with the States of Arizona, California, Idaho, Nevada, New Mexico, Texas, and Utah. Each of these States was represented by members of the Basin and Range Province Working Group. The cooperating agencies in each State and members and alternates of the Province Working Group are listed following the title page. Frank E. Kottlowski of New Mexico, Susan L. Tingley of Nevada, and Don R. Mabey of Utah, alternate members of the Province Working Group, contributed significantly to the regional phase of the study. The following individuals provided continuing advice and assistance to the Basin and Range

FIGURE 2.—View northward from Tatow Knob in the House Range with Tule Valley on the left; Fish Springs Range, central distance; Fish Springs Flat, middle right; and Granite Mountains on horizon, on right. The Great Salt Lake Desert lies to the north beyond Fish Springs Range. Thick carbonate beds of Cambrian age in the House Range, foreground, are fractured and contain solution channels. Photograph by W.D. Johnson (1901).

Province Working Group and in overall planning and execution of the work in preparation of this series of reports: John W. Hawley and William J. Stone of the New Mexico Bureau of Mines and Mineral Resources; Robert B. Scarborough of the Arizona Bureau of Geology and Mineral Technology; T.L.T. Grose of the Nevada Bureau of Mines and Geology and the Colorado School of Mines; and George Dinwiddie and George I. Smith of the U.S. Geological Survey. The authors acknowledge the review and insights into the ground-water hydrology offered by Harry D. Goode, consultant to the Utah Geological and Mineral Survey, and Joseph S. Gates of the U.S. Geological Survey.

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GEOLOGY

By K.A. SARGENT and DON R. MABEY[1]

STATIGRAPHY

In the Bonneville region (fig. 3), the exposed rocks include a wide variety of sedimentary, metamorphic, and intrusive and extrusive igneous rocks, ranging in age from Precambrian to Holocene. The principal lithologic characteristics of these rocks are summarized in figure 4. This section of this report on stratigraphy is taken largely from three excellent reports: (1) "Geologic history of Utah," by Hintze (1973); (2) "Geology of Nevada," by Stewart (1980); and (3) "Stratigraphy of the Great Basin region," by Stokes (1979).

PRECAMBRIAN

Sedimentary and metasedimentary rocks of Precambrian age crop out in the Deep Creek, Thomas, and Dugway Ranges and the Sheeprock and Cricket–northern San Francisco Mountains, all in Utah, and in the Snake Range in Nevada. Precambrian granitic rocks crop out in the Granite Peak area in the northern part of the Bonneville region.

All the sedimentary rock sections are thick, 1,100 m to greater than 3,700 m. The rocks are slightly metamorphosed argillite, quartzite, and tillite in the upper part of the Proterozoic. In the northern part of the region, in the Deep Creek and Snake Ranges, the oldest exposed sedimentary rocks are the McCoy Creek Group (Hintze, 1980), which consists of thick (3,750 m), alternating argillite and quartzite. In the Sheeprock Range, the lowest part of the Sheeprock Group (Hintze, 1980) contains 825 m of phyllite overlain by 425 m of quartzite, Dutch Peak Tillite (1,220 m) (Cohenour, 1959), argillite (760 m), and more quartzite (460 m). At the top of the Proterozoic is the Mutual Formation consisting of 60 m of argillite overlain by 215 m of quartzite. To the south in the San Francisco Mountains, the sedimentary rock sequence is similiar although somewhat thinner. Crittenden and others (1971) divided the upper part of the Proterozoic section into pre-tillite and post-tillite sequences. Pretillite sedimentary rocks were correlated by Crittenden and others (1972) with the Belt Supergroup of Montana and the Grand Canyon Supergroup of Arizona. Post-tillite rocks were correlated with the Windermere Group of western Canada. Deposition of the post-tillite sedimentary rocks probably began 750–850 m.y. ago and continued into the Cambrian in some areas. Upper Proterozoic and Lower Cambrian clastic marine sedimentary rocks were deposited in great thicknesses along the Cordilleran miogeosyncline of western North America. The axis of the thickest deposition lies near the Utah-Nevada boundary (Stewart, 1972). Diamictites, such as the Dutch Peak Tillite, may represent a Late Proterozoic period of glaciation in western North America.

Precambrian leucocratic granite of Granite Peak crops out in the northernmost part of the Bonneville region in Utah. Fowkes (1964) reported that the rock is extensively jointed and cut by numerous pegmatite dikes and quartz veins. The granite is in contact on the south with a large mass of biotite gneiss. Both the granite and biotite gneiss are shown as Early Proterozoic age. These are the oldest exposed rocks in the region and may be of equivalent age to Early Proterozoic quartzite and schist in the Ogden, Utah, area.

PALEOZOIC

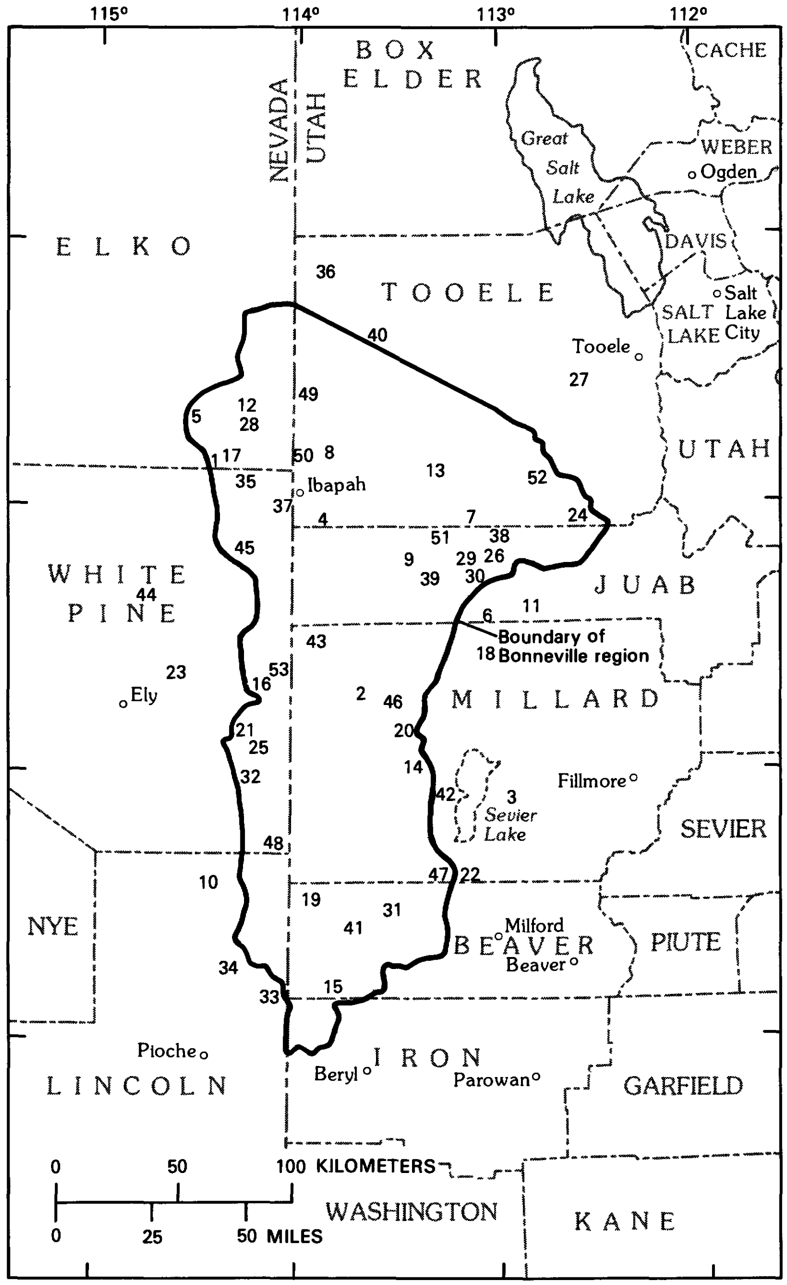
CAMBRIAN

Cambrian strata are widely distributed in the Bonneville region. They fall into a definite sequence: basal sandstone or quartzite (Prospect Mountain and Tintic Quartzites; maximum thickness of 3,100 m in the Drum Mountains, but generally about 1,000 m thick), overlain by the thin (45–150 m thick) Pioche Shale followed by a thick (1,800 m) carbonate sequence (generally limestone below, dolomite above). Thick, mottled, muddy limestones and thinly laminated stromatolitic dolomites were deposited in very shallow marine waters which deepened westward. The total thickness of Cambrian rocks exceeds 3,000 m (locally more than 3,700 m). They are thickest along a broad trough extending north-northeastward from about lat 38° N. at the Utah-Nevada boundary to the Utah-Idaho border north of the Great Salt Lake.

ORDOVICIAN

Ordovician strata are thick in the Bonneville region. Areas of greatest deposition nearly coincide with the Cambrian zone of abrupt thickening which is west of the central Utah craton in the Nevada-Utah miogeocline. Ordovician rocks may be divided into a consistent

[1]Utah Geological and Mineral Survey.



EXPLANATION

1 ANTELOPE RANGE
2 CONFUSION RANGE
3 CRICKET MOUNTAINS
4 DEEP CREEK RANGE
5 DOLLY VARDEN MOUNTAINS
6 DRUM MOUNTAINS
7 DUGWAY RANGE
8 DUTCH MOUNTAIN
9 FISH SPRINGS RANGE
10 FORTIFICATION RANGE
11 FUMAROLE BUTTE
12 GOSHUTE MOUNTAINS
13 GRANITE PEAK
14 HOUSE RANGE
15 INDIAN PEAK RANGE
16 KERN MOUNTAINS
17 KINGSLEY MOUNTAINS
18 LITTLE DRUM MOUNTAINS
19 MOUNTAIN HOME RANGE
20 NOTCH PEAK
21 SACRAMENTO PASS
22 SAN FRANCISCO MOUNTAINS
23 SCHELL CREEK RANGE
24 SHEEPROCK MOUNTAINS
25 SNAKE RANGE
26 SPOR MOUNTAIN
27 STANSBURY MOUNTAINS
28 SUGAR LOAF PEAK
29 THOMAS RANGE
30 TOPAZ MOUNTAIN
31 WAH WAH MOUNTAINS
32 WHEELER PEAK
33 WHITE ROCK MOUNTAINS
34 WILSON CREEK RANGE
35 ANTELOPE VALLEY
36 BONNEVILLE SALT FLATS
37 DEEP CREEK VALLEY
38 DUGWAY VALLEY
39 FISH SPRINGS FLAT
40 GREAT SALT LAKE DESERT
41 PINE VALLEY
42 SEVIER DESERT
43 SNAKE VALLEY
44 STEPTOE VALLEY
45 TIPPETT VALLEY
46 TULE VALLEY
47 WAH WAH VALLEY
48 BIG SPRING
49 BLUE LAKE SPRINGS
50 DEEP CREEK
51 FISH SPRINGS
52 GOVERNMENT CREEK
53 KERN MOUNTAIN SPRING

FIGURE 3.—Geographic index map of the Bonneville region, Utah and Nevada.

three-fold succession: (1) Lower Ordovician clastic limestones, (2) Middle Ordovician quartz sandstones, and (3) Upper Ordovician dolomites. Two subbasins developed in the Ordovician: the Ibex basin in the south where as much as 1,550 m of Ordovician strata were deposited and the North Utah basin outside of the Bonneville region where as much as 1,700 m of Ordovician is present. The northeast-trending Tooele arch separates the two basins (fig. 5).

Lower Ordovician limestone generally contains a large percentage of fine quartz sand and silt, and the limestone itself is commonly clastic. The carbonate units commonly contain intraformational conglomerate where newly deposited silty limestone layers are believed to have been eroded by tidal-flat currents and redeposited as pebbles at nearly the same location.

These Lower Ordovician shallow-water limestones are as thick as 1,200 m; they compose the lower

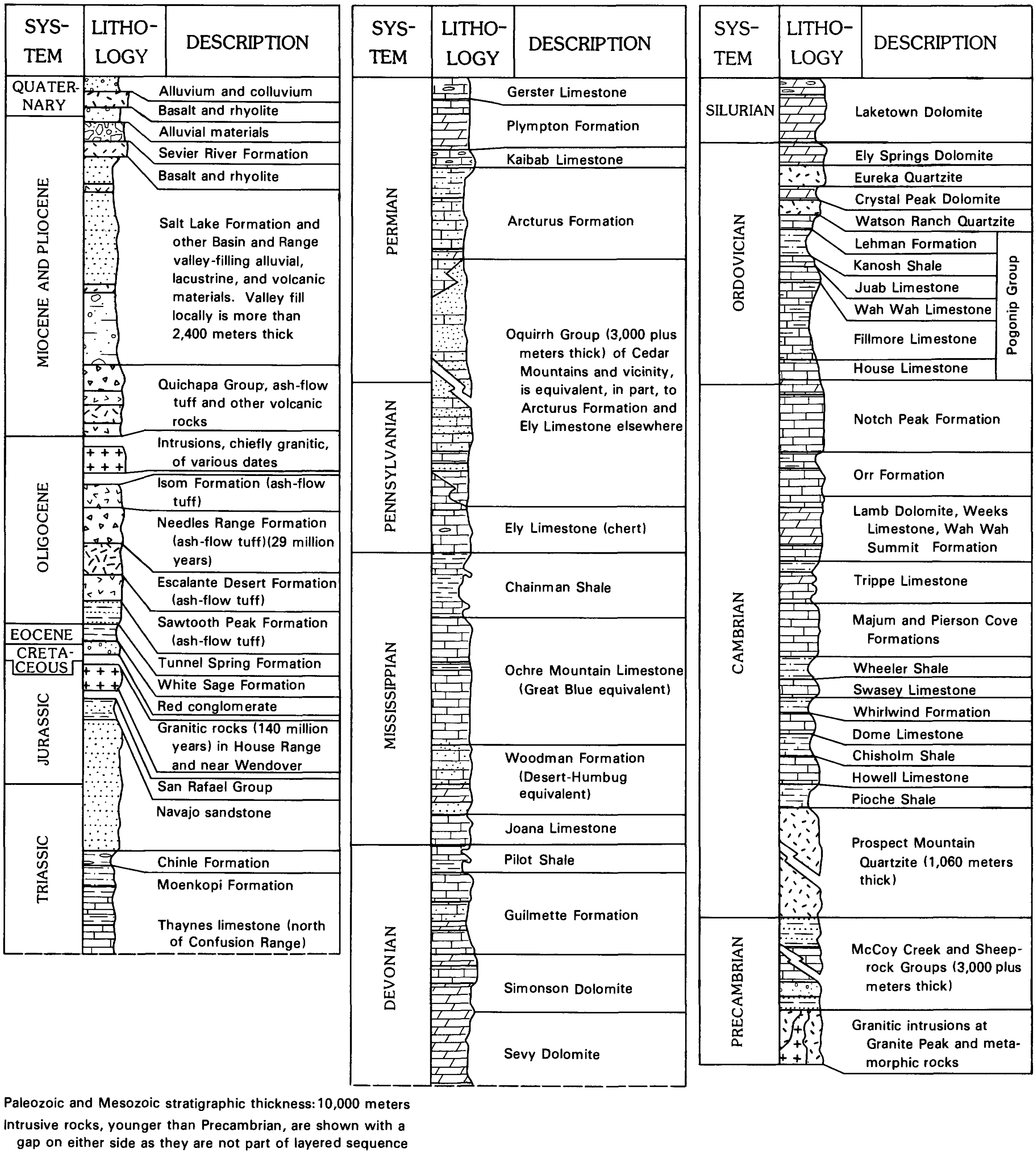


FIGURE 4.—Principal lithologic units and their ages in the Bonneville region, Utah and Nevada (modified from Hintze, 1980).

two-thirds of most of the Ordovician stratigraphic sections.

Middle Ordovician quartzites (Eureka and Swan Peak Quartzites) form distinctive orange-brown cliffs, sandwiched between gray and black underlying and overlying carbonate rocks. The quartzites are thickest in the Ibex basin (275 m) and North Utah basin (about 365 m), but are not present on the Tooele arch.

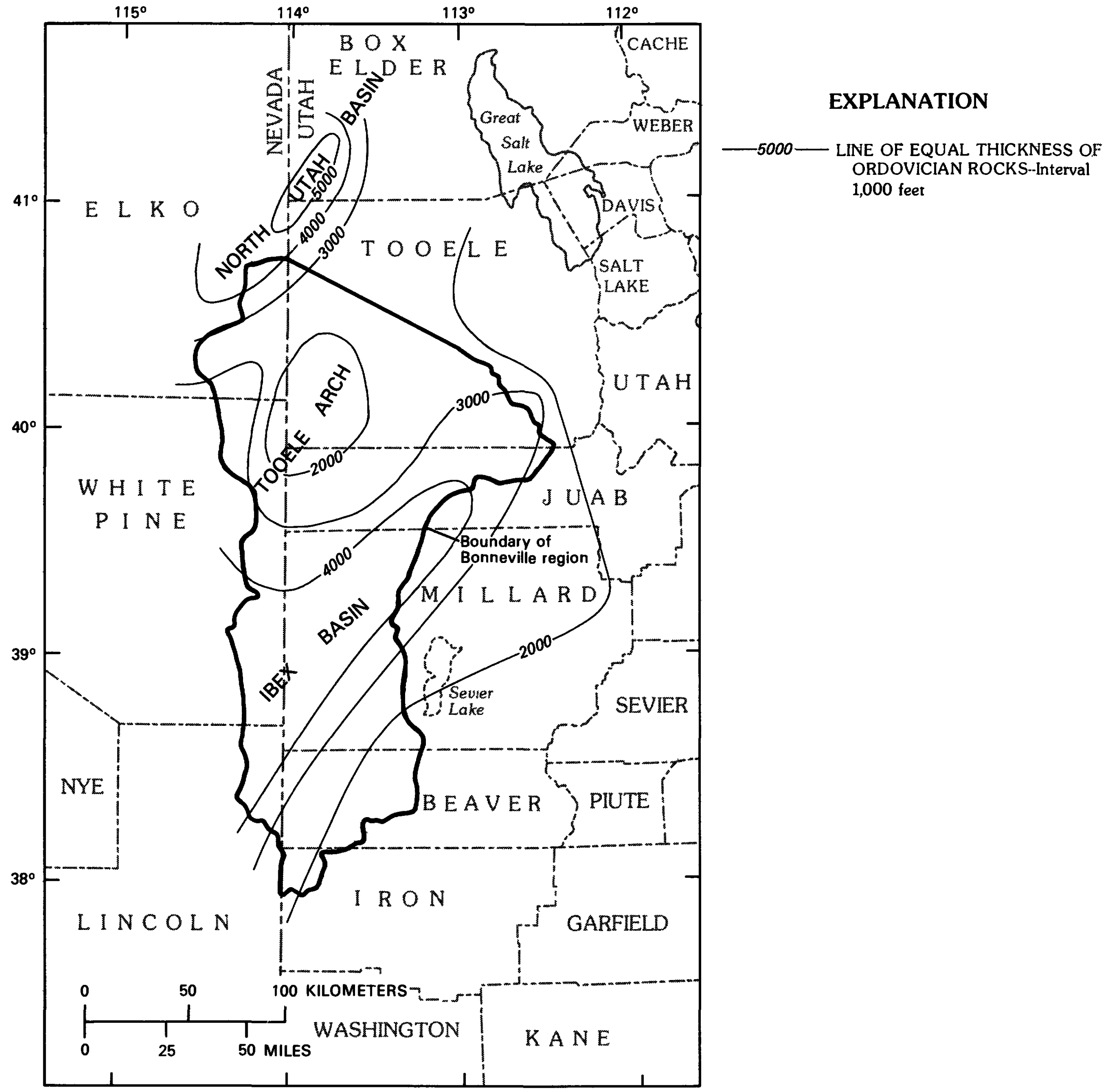


FIGURE 5.—Isopachs of Ordovician rocks and basins of deposition, separated by the Tooele arch, in the Bonneville region and vicinity, Utah and Nevada. Thicknesses in feet. Modified from Stewart (1980) and Hintze (1973).

Upper Ordovician dolomites (Fish Haven and Ely Springs Dolomites) are uniform, dense, cliff-forming units. These strata are thickest, about 215 m, in the Ibex basin.

SILURIAN

Silurian stratigraphy consists of one lithology, dolomite, assigned mostly to the Laketown Dolomite and part of the overlying Sevy Dolomite. Silurian strata are thin in eastern and southern parts of the Bonneville region but attain thicknesses as great as 400 m in the Ibex and North Utah basins.

DEVONIAN

Devonian rocks attain their maximum thickness (1,800 m) along the former axis of a miogeocline which trended northeastward through the Bonneville region. They thinned drastically eastward onto the craton which was less than 160 km to the east. The Devonian rocks show continuous marine deposition in western Utah and eastern Nevada. In Late Devonian time, however, the Stansbury Uplift, a mini-orogeny developed at the same location as the Tooele arch, caused the development of an erosional surface which cut out part of the earlier deposited Devonian and, east of the Bonneville region, beveled off rocks as old as Lower Cambrian. As much as 520 m of coarse conglomerate, the Stansbury Formation, was laid down in the vicinity of the uplift.

Rocks of Devonian age include, in ascending order (thicknesses are approximate), the upper part of the Sevy Dolomite (150 m); the Simonson Dolomite (3,000 m); the Guilmette Formation composed of dolomite, siltstone, and limestone (1,200 m); and the Pilot Shale, which in this region is dolomite, limestone, and sandstone (150 m).

Mississippian

The Oquirrh basin developed in the northern part of the Bonneville region in Mississippian time. The basin is in about the same location as the earlier, Devonian Stansbury Uplift and the Ordovician-Silurian Tooele arch. In the Mississippian Period the area became a shallow but steadily subsiding basin.

To the west in central Nevada, the Antler orogenic highland developed and the Roberts Mountain thrust was emplaced in Late Devonian and Early Mississippian time. From the Antler orogenic highlands, terrigenous detrital sediments accumulated in the foreland basin located east of the orogenic belt. The Bonneville region borders this foreland basin, and the Nevada portion of the region received Antler flysch deposits of fine-grained sediment which had their origin to the west. Just to the east of the flysch deposits, still in the Bonneville region, the Oquirrh basin was mainly receiving thick shelf-carbonate deposits. The Oquirrh basin received over 1,800 m of sedimentary rocks, largely carbonate but locally siltstone, sandstone, and some thick shales.

The Bonneville region has a complex Mississippian depositional history. Much of the area has the following sequence: Lower Mississippian strata consisting of the upper part of the Pilot Shale and Fitchville Formation (150 m) overlain by the Joana and Gardison Limestones (120 m); and Upper Mississippian strata consisting of the Great Blue Formation (460 m), mostly limestone, but with a thick shale sequence in the middle, and the Chainman and Manning Canyon Shales (460 m) sequence of mud and fine sand. To the west in Nevada, the Chainman is overlain by the Diamond Peak Formation (sandstone and limestone). The southern part of the Bonneville region was uplifted in late Mesozoic and although most, if not all, of the Mississippian rocks were stripped from the upper plate, the possibility exists that upper Paleozoic rocks may be present in a lower plate.

Pennsylvanian

In Pennsylvanian time the Oquirrh basin continued to dominate the depositional history of western Utah. In the Sheeprock Mountains at the northeastern end of the Bonneville region the marine Oquirrh Group or Formation (limestone and sandstone) is over 2,900 m thick. Elsewhere in the region, the Pennsylvanian limestones and sandstones are much thinner (Ely Limestone, 425–610 m). Identifying the source of the sands composing the Pennsylvanian in this region is somewhat of a puzzle. They are clean, fine grained, and quartzose, and their source must have been substantial, considering the large quantity deposited. Bissell (1959) suggested that some of it came from the Antler Orogenic Belt of central Nevada.

Permian

The Oquirrh and Ely basins dominated the depositional history of western Utah and eastern Nevada in Permian time. More than 1,770 m of carbonate, sandstone, and minor gypsum and chert were deposited in the area of the Deep Creek Mountains and the Confusion Range, which were then part of the Ely basin. At the northern end of the Bonneville region, the Oquirrh basin received over 2,150 m of limestone and sandstone that form the upper part of the Oquirrh Group (limestone and sandstone), the Kirkman Limestone, the Grandeur Formation (limestone and sandstone), the Meade Peak Member of the Phosphoria Formation, and the Franson Member of the Park City Formation (cherty limestone).

MESOZOIC

Triassic

The Lower Triassic Thaynes Limestone represents the last marine deposit in the western Utah and eastern Nevada miogeocline. In the Confusion Range, the Thaynes consists of more than 575 m of limy shales. Farther north in the Deep Creek Range only about 15 m of the Thaynes Limestone is present.

Jurassic

The only Jurassic sedimentary rocks exposed in the region occur in the southern Wah Wah Mountains at the southeastern edge of the Bonneville region. Here some Navajo Sandstone of Triassic(?) and Jurassic age is exposed in a window through an overriding thrust plate of Cambrian rocks.

Coarse-grained granitic rocks occur as stocks, plutons, and small intrusive bodies in the Bonneville region of Utah and Nevada. In Utah, two bodies have been radiometrically dated. A quartz-monzonite stock lies at the northern part of the region near the northern end of the Deep Creek Mountains; the southern part of this stock has been dated at 152 m.y. old by Stacey and Zartman (1976). To the south in the House Range, a porphyritic quartz monzonite dated at 143 m.y. old by Armstrong and Suppe (1973) intrudes Cambrian sedimentary rocks. In the southern Snake Range in Nevada near Wheeler Peak, five quartz-monzonite bodies of Jurassic age intrude Precambrian metasedimentary and Cambrian sedimentary rocks. More than 50 radiometric ages have been run on these rocks; Lee and others (1970) believed these rocks to be 156–160 m.y. The only other dated Jurassic stock is located in the Goshute Mountains near Sugar Loaf Peak. Here a quartz-monzonite stock that intrudes Devonian sedimentary rock was reported to have an age of about 140 m.y. (Schilling, 1965). Other undated intrusive bodies may be of Jurassic age, but also may be as young as Tertiary age. These intrusions are designated as Tertiary-Jurassic granitic rocks (TJgr) by Stewart and Carlson (1978) on the Geologic Map of Nevada.

Cretaceous

No Cretaceous sedimentary rocks are known in the Bonneville region; several Cretaceous plutons, however, have been reported in the Nevada part of the region. In the northern Antelope Range of Nevada, for example, monzonite and syenite stocks intrude Permian limestone and shale; the largest stock has been reported as 125 m.y. old by Schilling (1965). In eastern White Pine County, Nev., a relatively large pluton in the Kern Mountains is of possible Cretaceous age. Radiometric ages on this pluton, however, are 23 m.y. (Miocene), 48 m.y. (Oligocene), and 72 m.y. (Cretaceous), as reported by Hose and others (1976). Fission-track work by C.N. Naeser of the U.S. Geological Survey (written commun., 1970, as cited by Hose and others, 1976) gave an age of 40 m.y. Other granitic bodies in the Bonneville region are possibly of Cretaceous age, but none have been dated as Cretaceous.

TERTIARY

Paleocene And Eocene

Sedimentary rocks of early Tertiary age include a 180-m-thick red siliceous conglomerate of the White Sage Formation in the Deep Creek Mountains of Utah and a few small exposures of Sheep Pass Formation (conglomerate, limestone, mudstone, siltstone, shale, and sandstone) in the southern Snake Range of Nevada.

The volcanic history of the Bonneville region began in late Eocene or early Oligocene time with the eruption of intermediate-composition pumice breccia and thick lava flows of pyroxene andesite, hornblende rhyodacite, and biotite-quartz latite. Thin layers of air-fall tuff and nonwelded pumice breccia are intercalated with these lava flows. It is difficult to obtain thicknesses for these rocks, but Hose and others (1976) estimated at least 600 m of lower Tertiary volcanics in the nearby Schell Creek Range in Nevada. The initiation of volcanism in this area was placed by Hose and others (1976) at about 38 m.y. ago, near the beginning of the Oligocene Epoch, and continued intermittently until about 17 m.y. ago.

Intrusive granitic rocks of early Tertiary (Paleocene and Eocene, 38–65 m.y.) age are rare in the Bonneville region. Only two intrusive bodies are known, both in the northern part of the Bonneville region. One is near Dutch Mountain in Utah where a quartz-monzonite stock has been dated by Stacey and Zartman (1976) at 38 m.y. old. The other is in the Antelope Range in Nevada along the Elko–White Pine County line. Here a quartz-monzonite stock that intrudes Cambrian limestone has a reported age between 33 and 41 m.y. (Schilling, 1965; McKee and Marvin, 1976). An isotopic age of 48.2 m.y. from the pluton in the Kern Mountains indicates that it may be early Tertiary, but other ages of 23 m.y. and 72 m.y. (Hose and others, 1976) show that its true age is uncertain.

Oligocene

Oligocene sedimentary rocks are rare in the Bonneville region and are restricted to a few thin units within thick sequences of silicic lava flows and tuffs. The sedimentary rocks probably represent deposition between volcanic eruptions. A few sedimentary exposures occur in the southern Snake Range in northeastern Lincoln County, Nev. None are known in the Utah part of the Bonneville region, but they probably exist as areally limited beds intercalated with volcanic rock.

At about 34 m.y. ago, the character of volcanic activity changed in the Great Basin. Voluminous eruptions of quartz-latitic and rhyolitic ash-flow tuffs and lava flows began and continued through the Oligocene and much of the Miocene Epochs until about 17 m.y. ago. In the southern Bonneville region, great thicknesses of these older lava flows and tuffs accumulated. The most widespread sequence of ash-flow tuffs in the Bonneville region belongs to the Needles Range Formation, which covers more than 34,000 km^2 in southwestern Utah and eastern Nevada. Measured thicknesses of this unit exceed 400 m in the Fortification Range of Nevada and 900 m in the Mountain Home Range of Utah. It reaches a maximum thickness of about 2,500 m in the Indian Peak Range of Utah. Best and others (1979) believed that much of the Needles Range Formation was extruded from the Indian Peak cauldron which has its center near Indian Peak. Elsewhere in the southern part of the Bonneville region, buried volcanic centers or calderas are the probable source of other lava, ash-flow tuff, and laharic breccia, such as the Tunnel Spring Tuff, Sawtooth Peak Formation, Escalante Desert Formation, and the Isom Formation. To the north, the Thomas, Keg, and Desert calderas (just north of the Sevier Desert, on the eastern edge of the Bonneville region) gave rise to other thick ash flows: The Mount Laird Tuff, as much as 500 m thick in Dugway Valley; the Dell Tuff, about 180 m thick; and the crystal tuff member of the Joy Tuff, also about 180 m thick. In the northern part of the Little Drum Mountains, laharic breccia as thick as 460 m has been reported by Leedom (1974).

Basaltic and andesitic lavas of Oligocene age are relatively sparse in the Bonneville region. Intrusive granitic rocks of Oligocene age (about 25–37 m.y.) have been dated in the northern Snake Range of Nevada. Here quartz-monzonite and granodiorite stocks have ages of 25 and 31 m.y. (Lee and others, 1970) and cut sedimentary rock types of Paleozoic age. The Indian Peak stock in the Indian Peak Range of Utah is probably Oligocene. This stock is quartz-monzonite porphyry and intrudes intracauldron ash-flow tuffs of the Needles Range Formation dated at about 29 m.y. (Grant and Best, 1979). Small dioritic intrusions in the Wah Wah Range may be of Oligocene age.

Miocene and Pliocene

Miocene and Pliocene sedimentary rocks are widespread and locally very thick in the Bonneville region. They commonly occur in downfaulted blocks and for the most part were probably deposited during or after the development of basin-and-range structure. These rocks contain a wide variety of fluvial and lacustrine deposits, usually along with large amounts of volcanic debris. They are generally light-colored conglomerate, sandstone, siltstone, mudstone, and limestone. Ash-flow and air-fall tuffs are commonly intercalated with fluvial and lacustrine sediments. The thicknesses of the Miocene and Pliocene sedimentary rocks ranges from about 15 to about 90 m in most exposures but locally have been found to be from 1,500 to 2,150 m thick, as at Sacramento Pass in the southern Snake Range; substantial thicknesses underlie many of the Cenozoic basins. Farther south in Lincoln County, Nev., the Panaca Formation is at least 425 m thick, and equivalent rocks elsewhere are probably even thicker. The Panaca Formation consists largely of lake beds of siltstone and clay shale.

In Utah, the Salt Lake Formation consists of valley-filling alluvium, volcanic materials, and lacustrine deposits of Miocene and Pliocene age. The unit is poorly exposed in the Bonneville region but exceeds 300 m in thickness to the east under the Sevier Desert. No doubt the Salt Lake Formation, or rocks of similar age and lithology, is as thick as several hundred meters in many valleys of the Bonneville region.

Early to middle Miocene and Pliocene volcanism is concentrated in two areas of the Bonneville region. To the north, just west of the Thomas Range at Spor Mountain, thick silicic lava flows (500 m), tuff breccia, and a few thin (60 m) ash flows were extruded about 21 m.y. ago. In the southern part of the Bonneville region, thick rhyolitic tuffs and lava flows continued to pile up in the southern Indian Peak Range, eastern Mountain Home Range, and eastern Wah Wah Mountains (all in Utah) and in the Wilson Creek Range in Nevada. Locally, as much as 760 m of dacitic and rhyolitic lavas and 120 m of ash-flow tuff (Condor Canyon Formation of the Quichipa Group, 21–24 m.y.) are present in the Indian Peak and Mountain Home Ranges. Farther east in the Wah Wah Mountains, nearly 600 m of quartz-latitic lava flows and 400 m of ash-flow tuff were extruded about 21–24 m.y. ago. In this area, Lemmon and Morris (1979) also mapped the basalt of Brimstone Reservoir. This unit, about 150 m thick, was dated by Best and others (1980) at 13.3 m.y. In the Wilson Creek Range in Nevada, as much as 300 m of Miocene ash-flow tuff is shown by Ekren and others (1977). It is uncertain which Miocene formations compose this thickness, but distribution maps of Cook (1965) indicate the thickest unit may be the Leach Canyon Tuff.

Near the end of the Miocene, as much as 700 m of upper Miocene alkali-rhyolitic domes and flows were extruded at Topaz Mountain in the Thomas Range (Lindsey, 1982). This episode, at about 6.5 m.y. ago, marks the last major silicic extrusive event in the Bonneville region. Andesitic and dacitic flows were extruded in the lowlands west of the Fish Springs Range. Here a date of 4.7 m.y. is shown by Luedke and Smith (1978), whereas Morris (1978) shows these flows as Oligocene. Other minor, scattered upper Miocene and Pliocene volcanics occur northeast of the Wah Wah Mountains and in the Deep Creek Mountains.

Intrusive granitic rocks of Miocene and Pliocene (25–2 m.y.) age are rare in the Bonneville region. One reported age for the Kern Mountain pluton was 23 m.y., but other dates on the same pluton (48 m.y. and 72 m.y.) (Hose and others, 1976) put doubt on its actual age. Reported ages for the Ibapah stock, a large body in the Deep Creek Range, were 18.7 and 22 m.y., but a third age of 71 m.y. indicates this altered biotite-adamellite stock could be much older (Armstrong, 1966, 1970). The stock is intensely fractured by six sets of joints. Other Tertiary intrusive bodies in the region may be of Miocene and Pliocene age, but because no dates have been run on them, no exact ages can be assigned.

TERTIARY AND QUATERNARY

Extensive, unconsolidated to partly consolidated sedimentary rocks form a veneer over more than half of the Bonneville region. These sediments are in the form of Quaternary and Tertiary lake and playa deposits, alluvial fans, colluvium, and stream alluvium. To a lesser extent the upper Cenozoic deposits form landslides, beach-ridge deposits, and sand dunes. Materials in these deposits grade from large toreva and other landslide blocks to coarse gravel and boulders near mountain fronts to fine silt, clay, and locally some evaporitic deposits in valley flats and playas. For the most part the thickness of Quaternary sediments is less than a hundred meters, but in a few areas thicknesses may approach 300 m.

Quaternary basalts and andesites in or near the Bonneville region are limited to one location just outside the area, east of the Little Drum Mountains at Fumarole Butte. Here a shield volcano composed primarily of basaltic andesite and covering about 100 km^2 has been dated at 0.88 m.y. (Peterson and Nash, 1980). No intrusive rocks of Quaternary age are known in the Bonneville region.

SUMMARY OF TECTONIC EVENTS

PRECAMBRIAN TECTONIC SETTING

Evidence of the early tectonic setting of the Bonneville region is recorded in sedimentary and metasedimentary rocks of late Precambrian and Early Cambrian age. Stewart (1980) reported shallow-water terrigenous detritus, mainly quartzite, argillite, and siltstone, being deposited to thicknesses between 3,000 and 6,000 m. Studies of cross-stratification in the coarser clastic units indicate dominantly westward transport. Stewart interpreted the sediments as continental-shelf deposits laid down in the Cordilleran miogeosyncline at what was then the western margin of North America.

EARLY AND MIDDLE PALEOZOIC TECTONIC SETTING

During early and middle Paleozoic time the region continued to subside with the deposition of shallow-water sediments in a westward-thickening wedge along the western margin of North America. In Ordovician time two well-defined, northeast-trending depositional basins formed, the Ibex basin and the North Utah basin, separated by the Tooele arch (fig. 5). These structures persisted through the Silurian. In the Devonian, a mini-orogeny, called the Stansbury disturbance, renewed emergence of the area of the Tooele arch, and an unconformity developed which beveled downward to rocks as old as Lower Cambrian east of the Bonneville region. Coarse conglomerate, the Stansbury Formation, formed near the uplift, and Devonian sands spread out from the distal edges of the conglomerate.

By Late Devonian and Early Mississippian time the Antler orogeny was dominant to the west in central Nevada. Deep-water siliceous sediments and volcanic-assemblage rocks were being uplifted and moved eastward as much as 145 km over shallow-water carbonate rocks along the Roberts Mountain thrust. This orogeny created the Antler highland from which coarse flysch sediment was shed to both the east and the west. The Bonneville region, more than 150 km to the east, received some fine-grained sediment from this highland, but the dominant lithology was still carbonate and shale. The Oquirrh basin began to form in the northern Bonneville region near the end of Mississippian time, and here, over 1,800 m of sedimentary rocks, largely limestone, were deposited in the Mississippian Period alone.

LATE PALEOZOIC AND MESOZOIC TECTONIC SETTING

For the Bonneville region, the tectonic setting from middle Mississippian to Early Triassic changed only in the configuration and size of depositional basins. The deepest part of the Oquirrh basin migrated eastward and received as much as 4,000 m of Pennsylvanian and nearly 3,000 m of Permian marine sediments. Also in Pennsylvanian and Permian time, the Ely basin formed southwest of the Oquirrh basin along the Nevada-Utah line. It received as much as 600 m of sediment in Pennsylvanian time and as much as 1,770 m in Permian time. The Thaynes Limestone represents the last marine invasion in the Bonneville region. In the southern Ely basin 580 m of Lower Triassic Thaynes Limestone is preserved. By the end of the Triassic, more than 10,000 m of sedimentary rocks had been deposited in the Bonneville region.

Marine deposition ended in the early Mesozoic when the large-scale, north-northeast-trending Sevier orogenic belt became active. Most of eastern Nevada and western Utah were in this belt of large-scale overthrusting, folding, and general uplift, which lasted from Middle Jurassic to the end of the Mesozoic. Thick wedges of Upper Jurassic and Cretaceous detritus were shed to the east and southeast from the uplift. Metamorphic terrane within the Bonneville region related to the Sevier orogeny is found in the Kern and Deep Creek Mountains and the northern Snake Range near the Utah-Nevada border. In the Snake Range, the geology is complex and consists of a metamorphosed core overlain by a nonmetamorphic allochthonous sequence. This area has been called a metamorphic core complex, one of a series in a north-trending zone across the western United States. The underlying rocks consist of upper Precambrian and Cambrian siliciclastic and carbonate rocks of low metamorphic grade and weak schistosity. A subhorizontal tectonic discontinuity or decollement separates the metamorphic core complex from the overlying, unmetamorphosed overthrust rocks. The date of the metamorphism is not clear, but perhaps it began as early as Jurassic and continued into Tertiary time. Metamorphism is present in the older rocks of the Kern and Deep Creek Mountains, but here the Snake Range decollement is not well expressed. Some of the largest granitic bodies in the region were intruded in Jurassic time (Stewart, 1980).

Cenozoic Tectonic Setting

In Paleocene and Eocene time, much of western Utah and eastern Nevada was elevated and shedding continental sediments to the east and south. In late Eocene or early Oligocene time, explosive volcanism started with extensive eruptions of ash-flow tuffs and intermediate-composition lavas, and numerous granitic stocks were emplaced. In western Utah, the Oligocene igneous activity occurred in three west-trending belts beginning in the north. The northern belt, which extends westward from Park City, Utah, is north and northeast of the Bonneville region. The middle (Tintic) belt extends into the northern part of the Bonneville region, and the southern (Marysvale and Pioche) belt is in the southern part of the region. Magnetic data indicate that within these igneous belts intrusive rock is much more abundant in the subsurface than in outcrop; nearly continuous batholith appears to underlie much of the Marysvale and Pioche belt. In Miocene and Pliocene time, volcanism continued. By middle Miocene, crustal extension and block faulting started to shape the Bonneville region into basin-and-range patterns similar to the ones seen today. Sedimentation began in the basins in the Miocene and has continued to the present. Basins commonly are underlain by sedimentary and volcanic rocks of Miocene and Pliocene age, concealed by Quaternary alluvium and lake beds. In addition to the local basin-and-range structure, a major regional depression, the Lake Bonneville Basin, developed in northwestern Utah. By Holocene time, this basin had a topographic closure of over 300 m and periodically contained major lakes.

STRUCTURAL GEOLOGY

Two major tectonic events contributed to the structural history of the Bonneville region: (1) Thrust faulting and folding during the Sevier orogeny in Middle Jurassic to early Tertiary time, and (2) middle to late Cenozoic regional extension and block faulting, sometimes called the Basin and Range event or orogeny.

THRUST FAULTING

Eastward-directed thrust faults and related folds of the Sevier orogeny affected the pre-Tertiary rocks of the Bonneville region. The structural style varies from place to place depending in part on the physical characteristics of the rocks involved and in part on the location within the affected belt. The Precambrian and lower Paleozoic sequence is generally composed of more massive and seemingly more competent quartzites and carbonate rocks. The upper Paleozoic rocks, although having great thicknesses of carbonate rock, also contain a large percentage of shale which is relatively soft and incompetent. The oldest important structural feature in the area is a large low-angle fault complex found in the Snake Range, Kern Mountains, and Deep Creek Range. This low-angle fault or detachment has been called the Snake Range decollement. It is well exposed in many places and extends throughout the Snake Range, which is more than 80 km long and more than 25 km wide. The lower plate is cut by intrusive bodies that locally metamorphosed the country rock. Rocks in the lower plate are Middle Cambrian or older and are only moderately faulted. Rocks in the upper plate are Middle Cambrian or younger and complexly faulted but are not cut by intrusives. The style of thrusting in the upper plate is that of younger over older so that the succession in ascending order is generally correct but large slices are cut out thereby greatly attenuating the geologic section. In addition, the upper plate shows a higher density of normal faults than the lower plate. This resulted in a horst-and-graben structure, a style compatible with development by horizontal tension during at least part of the Sevier orogeny.

Further east, the style of thrusting changes with older (lower Paleozoic and Precambrian) rocks over younger (upper Paleozoic and Mesozoic) rocks. In this area, several thrusts have been mapped at the surface and more have been identified in reflection seismic data. A Consortium for Continental Reflection Profiling (COCORP) seismic reflection profile (Allmendinger and others, 1983) extending east from the Snake Range reveals a series of remarkably continuous low-angle reflectors extending to depths of 15–20 km. These reflections may represent major detachments developed during the Sevier orogeny. Windows in the thrust plates as far west as the Wah Wah Mountains reveal Mesozoic rocks underlying Paleozoic rocks. The possibility exists that the Paleozoic and Precambrian rocks cropping out in the eastern and central part of the Bonneville region are in thrust sheets overriding Mesozoic sedimentary rocks.

FOLDS

Folds are surprisingly scarce in the region and appear to be restricted largely to structural troughs. The trends of principal folds within the structural trough areas, as in the Confusion Range in Utah and west of the region in the Butte structural trough, generally parallel the axis of the trough. In these two examples, both folds and axes have a northerly trend. The folds are formed in upper Paleozoic rocks that contain thick incompetent units. They are believed to have formed during late Mesozoic to early Cenozoic time. During folding in the Confusion Range, two decollement-type faults developed. Rocks in the thrust plates glided toward the structural trough axis forming complex secondary folds and lobes (Hose, 1977).

BASIN-AND-RANGE FAULTING

The topography of the Basin and Range province is one of north-trending elongate mountain ranges flanked by nearly flat bottomed valleys or basins. This pattern was formed by the Basin and Range orogeny which began about 17 m.y. ago in response to regional extension. The vertical displacement on these faults is as great as 4,500 m or more. Movement along these faults is the primary cause of earthquakes in the region. Most of the earthquakes occur at shallow depths with 90 percent shallower than 10 km. The Bonneville region lies west of the intermountain seismic belt, but earthquakes are recorded in the region and evidence of local Quaternary faulting exists.

Stewart (1971, 1978) recognized three basic models of basin-and-range structure: (1) A system of structural blocks rotated along curving, downward-flattening listric faults; here the uptilted part of the block forms the mountains and the downslope area is the valley; (2) simple horsts and grabens; and (3) a system of elongate rhombohedral blocks formed by fragmentation of the upper crust by high-angle faults. There is no unanimous opinion on which model is dominant over the province; one or more models are likely relevant in any given area. In western Utah, the seismic reflection and earthquake data strongly suggest that the listric style is dominant. Many basin-and-range faults flatten at depth and appear to merge with the older, low-angle thrust faults. Apparently the current extension of the upper crust in this region is occurring along the same structures that formed during crustal shortening in Mesozoic time.

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POTENTIAL HOST MEDIA FOR RADIOACTIVE WASTE

By K.A. Sargent

Potential host media for a mined repository for isolation of high-level radioactive waste in the Bonneville region, Utah and Nevada, include intrusive rocks such as granite; ash-flow tuff, especially where densely welded and greater than 100 m thick; and basalt and basaltic andesite lava flows where greater than 100 m thick. In addition, basin-fill deposits and possibly other rock types have potential as host media in the unsaturated zone. Salt and other evaporitic deposits are not known to have potential as host media in this region. Plate 2 shows the outcrop areas of potential host media and areas believed to have thick unsaturated zones in the Bonneville region.

INTRUSIVE ROCKS

Granitic rocks in the Bonneville region occur as widely scattered, mostly small exposures. The rocks are of Mesozoic, Tertiary, and Precambrian age and are summarized by Jenness (1984a).

The Indian Peak quartz-monzonite stock of Tertiary age crops out in the southern part of ground-water unit BV–01 and is heavily altered to propylite. The Cactus stock, a quartz-monzonite tabular intrusive of Tertiary age, crops out in the San Francisco Mountains in the southeastern part of ground-water unit BV–01. A 143-m.y.-old (Mesozoic) porphyritic-quartz-monzonite intrusive crops out north of Notch Peak in the northeastern part of ground-water unit BV–01; the southwestern part of the mass is a sill and the main part is an extensively jointed stock. Jurassic and Cretaceous to Tertiary quartz-monzonite intrusive rocks crop out in the Snake Range in the northwestern part of ground-water unit BV–01 and southwestern part of ground-water unit BV–02. The area is believed to be part of a metamorphic core complex and probably is underlain by a regional detachment fault. Some of the granite has been metamorphosed to a gneiss, perhaps during thrusting.

Outcrops of intrusive rocks in the western part of ground-water unit BV–02 in the Kern Mountains are Tertiary and Cretaceous granodiorite and quartz monzonite having steep north-trending fractures. The Ibapah stock of Tertiary age (18–22 m.y.) crops out in the Deep Creek Range at the junction of ground-water units BV–02 and BV–04. The mass, a quartz-monzonite intrusion, is reported to be intensely fractured. The Gold Hill quartz-monzonite stock is in the northern part of the Deep Creek Range in ground-water units BV–02 and BV–04. The stock is composed of both Jurassic (152 m.y.) and Tertiary (40 m.y.) intrusive masses. Surface exposures of the stock locally show three planes of fracturing (fig. 6) and deep weathering.

Two stocks crop out in the eastern part of ground-water unit BV–03. To the southeast, Tertiary granitic intrusive rocks form much of Desert Mountain. Magnetic surveys indicate the stock may have intruded part of a large caldera. The other stock is the Sheeprock granite of Tertiary age in the Sheeprock Mountains; this stock is cut by numerous joint sets. No description is available for a third small intrusion in the northeastern part of ground-water unit BV–03.

A small Tertiary quartz-monzonite stock of uniform texture crops out in the Kingsley Mountains in the west-central part of ground-water unit BV–04. Two quartz-monzonite stocks occur east of Antelope Valley in ground-water unit BV–04. The one southwest of Sugar Loaf Peak is of Jurassic age, and the one on the divide between ground-water units BV–04 and BV–05 at the Nevada-Utah border is Tertiary to Jurassic in age. In the Dolly Varden Mountains in the northwestern part of ground-water unit BV–04, monzonites and syenites of Tertiary and Cretaceous age crop out.

TUFFACEOUS ROCKS

The southern Bonneville region was the site of extensive volcanism in Oligocene and Miocene time. Exposed, and probably buried, calderas gave rise to sequences of

FIGURE 6.—Outcrop of quartz monzonite showing three fracture planes, east of Gold Hill, Deep Creek Range, Tooele County, Utah. Photograph by M.S. Bedinger (1984).

ash-flow tuff that may exceed 5,000 m in aggregate thickness. Ash-flow tuffs in the Mountain Home and Indian Peak Ranges in the southern part of ground-water unit BV–01 are the thickest in the region. The Needles Range Tuff was extruded from a caldera complex in the Indian Peak Range and accounts for more than 2,500 m of the tuff in that area. Ash-flow tuff thickness in the White Rock Mountains of Nevada in the southwestern part of ground-water unit BV–01 and in the San Francisco Mountains of Utah in the southeastern part of ground-water unit BV–01 are approximately 500–1,000 m thick. Scattered small outcrops of ash-flow tuff 500 m thick crop out in the central part of ground-water unit BV–01. Aggregate tuff thicknesses decrease to the north away from the caldera complex in the Indian Peak Range.

In the northern half of the Bonneville region parts of the Thomas, Dugway Valley, Keg, and Desert calderas are present in southern and southwestern parts of ground-water unit BV–03. As much as 1,000 m of ash-flow tuff may be present in and near the calderas, but flows become very thin short distances away from their source areas. Ash-flow tuffs in the Bonneville region are summarized by Roggensack and Jenness (1984).

BASALTIC ROCKS

Basalt flows of Miocene age, with total thicknesses as much as 150 m, crop out at the southern end of Wah Wah Valley in the southeastern part of ground-water unit BV–01.

Numerous small erosional remnants of basalt flows as much as 60 m thick crop out west and southeast of the Fish Springs Range in ground-water units BV–02 and BV–03. Basaltic rocks of the Bonneville region are summarized by Jenness (1984b).

ARGILLACEOUS ROCKS

Shales and other argillaceous units are common and widely distributed throughout the Bonneville region (Johnson, 1984). Shales thicker than 150 m are known in Precambrian, Cambrian, Ordovician, Devonian and Mississippian, and Triassic sections. Because of the structural complexities caused by folding and faulting, argillaceous rocks in the region do not appear to have potential as host rocks. It is presumed, however, that the rocks would serve as sorptive zones for radionuclides and would slow traveltimes of ground-water flow from a repository to its discharge area.

Thick slate and argillite occur in the Sheeprock and McCoy Groups of Precambrian age (Hintze, 1980) in ground-water units BV–01, BV–02, BV–03, and BV–04. Other thick shales occur in ground-water units BV–01, BV–02, and BV–04 in Cambrian Pioche Shale, Ordovician Kanosh Shale, Mississippian and Devonian Pilot Shale, and Mississippian Chainman Shale. In the Confusion Range, more than 570 m of Triassic Thaynes Limestone, containing thick claystone and siltstone, is present but is highly faulted.

UNSATURATED ZONE

Nearly all the ranges in the region have unsaturated zones that are probably greater than 150 m thick.

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QUATERNARY TECTONISM

By K.A. SARGENT and DON R. MABEY[2]

Quaternary tectonism in the Bonneville region is evidenced by seismic activity, above-normal heat flow, Quaternary faulting, late Cenozoic volcanic activity, and active vertical movement. Figure 7 is a composite illustration depicting each of these features in a generalized format at a scale of approximately 1:2,500,000.

SEISMICITY

The Bonneville region lies west of the intermountain seismic belt, and only a few dozen earthquakes have been reported for the region (Richins, 1979). Most occurred in two swarms; one was in late 1963 and early 1964, in the west-central part of the region, in the Snake Range of Nevada, with a maximum Richter magnitude (surface wave) of 3.9. The other was in 1974, 1975, and 1976, in the northeastern part near the Thomas Range, with a maximum Richter magnitude of 2.2 (fig. 7). All but two earthquakes in the region were less than Richter magnitude 4. The largest earthquakes were two Richter-magnitude-4.3 events. One, in 1894, apparently was near the young fault scarps on the eastern side of the Fish Springs Range. The other, in 1915, was near the Nevada-Utah line near Ibapah, Utah. The swarm of earthquakes in the west-central part of the region may be associated with the Snake Range decollement, a low-angle detachment surface, recently discussed by Allmendinger and others (1983). Contours showing the greatest strain release in the region are centered on the earthquake swarm in the Snake Range and on the earthquake near Ibapah (Algermissen and others, 1983) (fig. 7). The swarms of scattered earthquakes in the northeastern part of the region affect the symmetry of the contour around Ibapah.

HEAT FLOW

Approximately 10 heat-flow readings have been reported in the Bonneville region (Sass and others, 1976; John H. Sass, U.S. Geological Survey, written commun., 1982). Most of the values are typical of the northern Basin and Range province, averaging about 2 HFU. Heat-flow values over 2.5 HFU occur in Fish Springs Flat and coincide with the swarm of earthquakes in the northeastern part of the region (fig. 7). The highest heat-flow value in the region, 9.29 HFU (Juab County), reflects a local geothermal anomaly.

QUATERNARY FAULTING

Nakata and others (1982) show widely scattered north- and northeast-trending, late Quaternary (less than or about 500,000 yr old) faults (fig. 7). One set of three faults, designated 10,000 yr old or less, occurs on the eastern side of the Fish Springs Range and west of the earthquake swarm in the northeastern part of the region.

LATE CENOZOIC VOLCANIC ACTIVITY

No volcanic rocks younger than about 2 m.y. are believed to crop out in the region. However, Fumarole Butte, a Quaternary basalt center, lies outside the Bonneville region about 16 km to the east in the Sevier Desert.

VERTICAL CRUSTAL MOVEMENT

Gable and Hatton (1983) show that the eastern half of the Bonneville region is rising at a rate of 2–4 mm/yr based on geodetic-leveling data. This uplift is believed to be due primarily to the continuing isostatic rebound following the removal of the water load of Pleistocene Lake Bonneville. On a more regional scale, the region is rising at the rate of 2–4 m per 10,000 yr (0.2–0.4 mm/yr) based on geology, geomorphology, and radiocarbon dates (fig. 7).

About 16,000 yr ago, Lake Bonneville inundated much of the northeastern part of the Bonneville region with water of maximum depths of over 300 m. The weight of the water depressed the northern part of the region a maximum of about 60 m. When the water load was removed, the surface gradually rebounded (and continues to rebound today). During the period that the deep-water lake existed, numerous lake features were formed. Erosion of the basin rim during the last deep-lake cycle lowered the outlet about 90 m, thus decreasing the maximum depth of a lake that can develop with the current topography. Over the last 10,000 yr, part of the northern edge of the region and the floors of closed topographic basins have been inundated periodically by shallow lakes.

[2]Utah Geological and Mineral Survey.

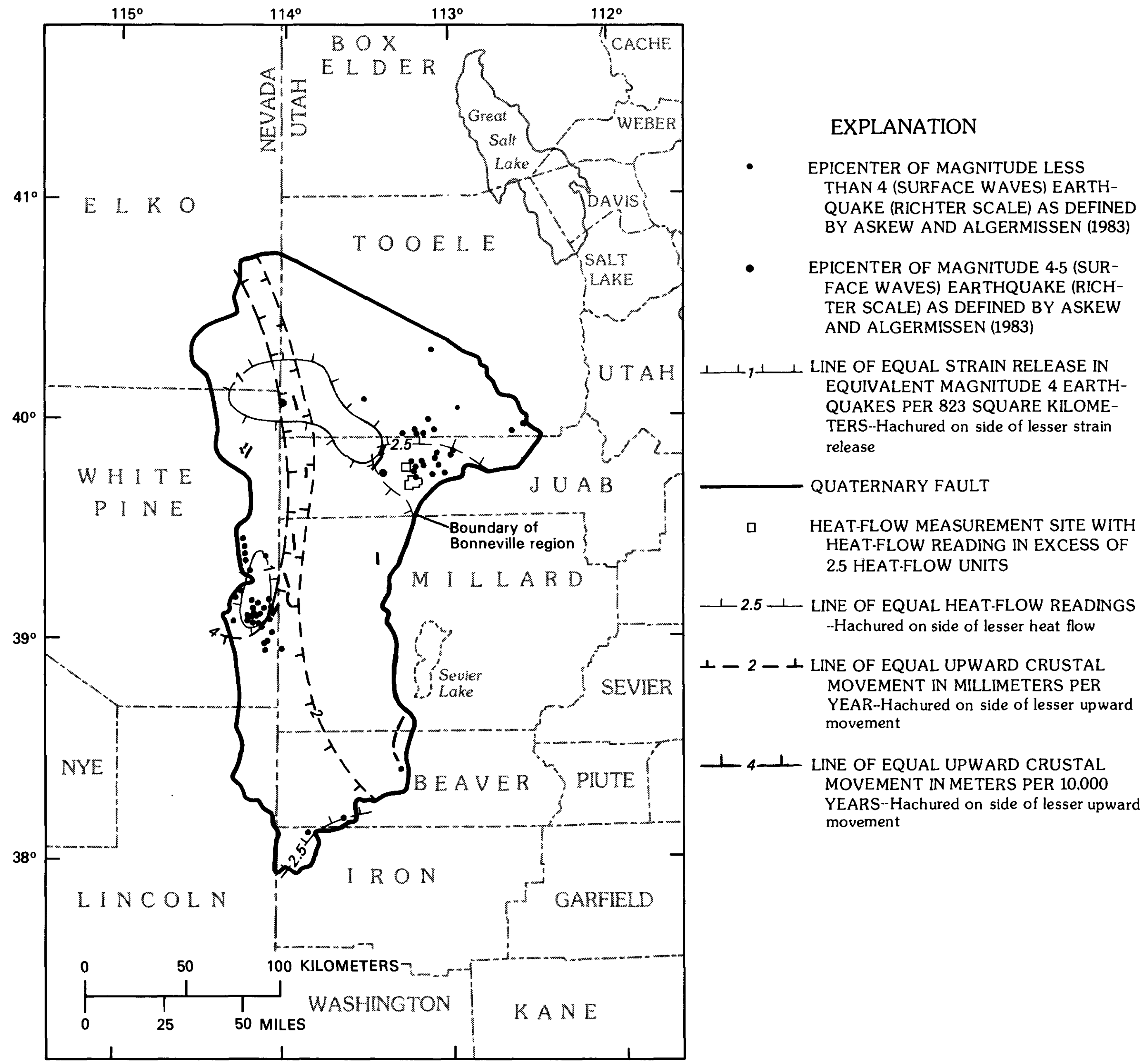

FIGURE 7.—Quaternary tectonic features of the Bonneville region, Utah and Nevada.

PHOTOLINEATIONS

Recent work by T.W. Offield (U.S. Geological Survey, written commun., 1983) on linear features in the Great Basin shows that virtually no photolineations occur in Quaternary sediments in the Bonneville region. The longest photolineations are range-front faults that probably originated 15–20 m.y. ago, and most of these show little or no renewed movement in the last 500,000 yr.

MODERN TECTONISM

The Bonneville region, along with the rest of the northern Basin and Range province, is extending in a generally east-west direction. No direct measure of the rate of extension within the region is available, but the relative scarcity of Quaternary fault scarps and historic earthquakes suggest that the extension rate is lower than the area to the east, nearer the border of the Basin and Range province. In response to the regional extension, vertical movement occurs along generally north-trending normal fault zones that bound the ranges. Most of these faults dip under the valleys and flatten at depth, and some appear to merge with detachments related to older thrusting. Earthquakes associated with movement along these normal faults are shallow (focal depths less than 10 km). Displacment along the fault zones is likely to drop the basin rather than elevate the range. Tilting of both blocks may be extensive.

The relatively rapid depression and rebound of the land surface accompanying the increase and decrease of the depth of Lake Bonneville appears to have occurred independent of movement along the major normal-fault systems. The vertical movement related to the lake was accommodated by horizontal movement of material with a relatively low viscosity at depths below which the brittle failure associated with earthquakes occurs.

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GROUND-WATER HYDROLOGY

By M.S. BEDINGER, J.E. REED and WILLIAM H. LANGER

The Bonneville region of Utah and Nevada is part of a large ground-water flow system that is integrated partly through basin-fill deposits, but largely through an underlying carbonate-rock sequence which serves as an underdrain. The region includes several topographically closed basins with no surface discharge—Pine Valley and Wah Wah Valley in ground-water unit BV–01; and closed basins with surface discharge by evapotranspiration—Tule Valley in ground-water unit BV–01 and Tippett Valley and Antelope Valley in ground-water unit BV–04. Drainage basins that are open to the Great Salt Lake Desert are Dugway Valley–Government Creek area and Fish Springs Flat in ground-water unit BV–03, Snake Valley in ground-water unit BV–01, Deep Creek Valley in ground-water unit BV–04, and small valleys in ground-water unit BV–05. The climate is arid to semiarid with annual precipitation ranging from 150 to 200 mm in the basin areas to a maximum of about 800 mm in the highest mountain ranges. Mean annual free-water-surface evaporation is approximately 1,000–1,500 mm/yr.

MAJOR HYDROGEOLOGIC UNITS

Basin fill (including alluvial material of stream valleys) occurs largely in structural basins and is as thick as 2,800 m. The more permeable part of the basin fill is generally in the upper 500 m of the section. Basin fill crops out at the surface over approximately two-thirds of the region. Bedrock pediment surfaces underlie the fill at shallow depths in many areas, such as in the Mountain Home Range (Needles Range) and western Tule Valley in ground-water unit BV–01 and in the Goshute Mountains in ground-water unit BV–05.

Basin fill consists mostly of nonindurated to semiindurated sedimentary terrestrial and lacustrine deposits and volcanic rocks. The ages of the deposits range from Tertiary to Holocene. The terrestrial deposits consist primarily of poorly sorted to moderately sorted mixtures of gravel, sand, silt, and clay that were derived largely from the consolidated rocks in the nearby mountains. The fill also locally contains fine-grained lake deposits, limestone, and evaporitic deposits; tuffaceous sediments and extrusive volcanic rocks from episodic volcanic activity; and glacial deposits from the Quaternary Period. The fill varies greatly both vertically and areally.

Volcanic rocks are grouped hydrologically as undifferentiated volcanic rocks and as tuffs. Undifferentiated volcanics include flows and tuffs of Tertiary age, as much as 1,200 m thick. Tuffs consist of ash-fall and moderately to densely welded ash-flow units. Tuffs of Tertiary age occur in the southern part of ground-water unit BV–01. Their aggregate thickness is over 3,000 m.

Consolidated fine-grained clastic rocks, composed of silt and argillaceous materials of Precambrian and Cambrian age, are scattered throughout the region. Thicknesses of the units mapped are more than 700 m. They are interbedded with other coarser sediments and are probably discontinuous due to attenuation faulting.

Carbonate rocks are widespread in the subsurface and at the surface. They consist of limestones, massive to thinly bedded, and dolomites with silty and sandy interbeds. Carbonate rocks ranging in age from Cambrian to Triassic are commonly intensively fractured, and some units exhibit well-developed solution openings (figs. 8, 9, 10, and 11). Aggregate thicknesses of carbonate rocks range from 150 m to 7,500 m. Carbonate rocks compose an extensive aquifer that underlies much of the region.

Orthoquartzites, metamorphics, and silicic intrusive rocks are exposed throughout the area and underlie much of the region. These rocks range in age from Precambrian to Tertiary.

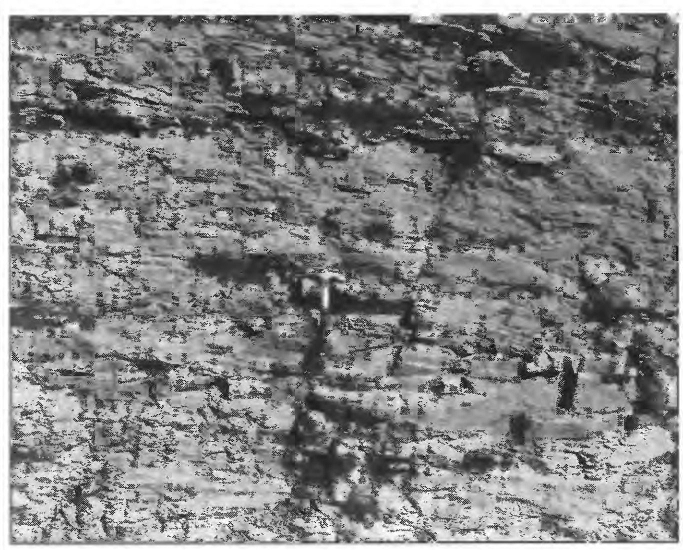

FIGURE 8.—Intensively fractured limestone and shaley limestone of the House Limestone of Ordovician Pogonip Group, near Skull Rock Pass, Millard County, Utah. Photograph by M.S. Bedinger (1984).

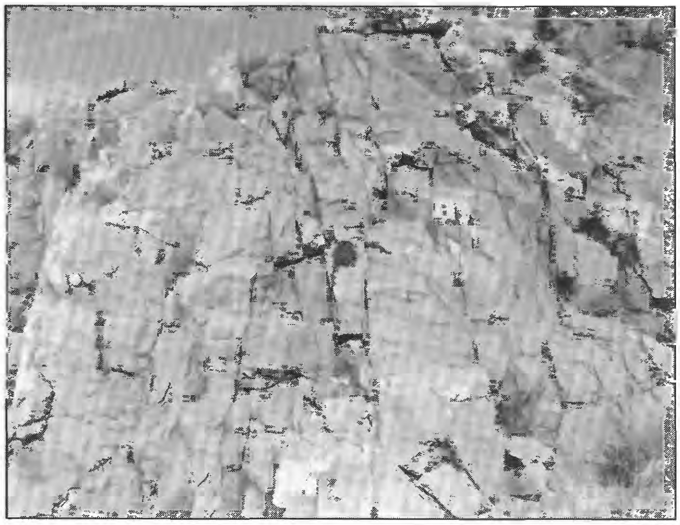

FIGURE 9.—Silurian Laketown Dolomite showing predominantly vertical fractures in the massively bedded dolomite, southern Confusion Range, Millard County, Utah. Light meter in center of photograph is about 7 × 10 centimeters. Photograph by M.S. Bedinger (1984).

FIGURE 10.—Limestone beds in the Devonian Guilmette Formation, with fracture sets at right angles to bedding planes, southern Confusion Range, Millard County, Utah. Photograph by M.S. Bedinger (1984).

GROUND-WATER FLOW REGIME

The source of recharge to ground water in the region is precipitation. Most of the precipitation falls at higher elevations in the mountain ranges, but most recharge probably occurs by infiltration of runoff as it leaves the mountains and crosses permeable basin-fill deposits. Recharge to most segments of the region has been estimated in reconnaissance studies using a method developed by Eakin and others (1951, p. 79–81) for use in Nevada and modified by Hood (Hood and Waddell, 1968, p. 22–23) for use in western Utah. Discharge of ground

FIGURE 11.—The Mississippian Joana Limestone showing well-developed solution channels parallel to bedding near Garrison, Millard County, Utah. Photograph by M.S. Bedinger, (1984).

water occurs largely to springs and by evapotranspiration in areas where the ground-water level is near the land surface.

Water budgets for the Bonneville region are given in reconnaissance reports for basins in the region and summarized in the report on the southern Great Salt Lake Desert by Gates and Kruer (1981). Gates and Kruer summarized and revised the water-budget estimates reported in previous reconnaissance reports on the basins in the region and provided estimates of water-budget components of the southern Great Salt Lake Desert. The water-budget analyses for basins in the Bonneville region show unmistakable evidence of interbasin ground-water flow, even considering that the estimation of individual waterbudget components is only approximate. For example, Tule Valley has an estimated recharge rate within the basin of 9.4 hm^3/yr (cubic hectometers per year) from precipitation. The estimated loss to evapotranspiration within the basin, based on three methods of estimation, ranges from 29.6 hm^3/yr to 69.0 hm^3/yr (Stephens, 1978). Fish Springs Flat has an estimated recharge rate of 5 hm^3/yr and an estimated discharge rate to springs of 43 hm^3/yr (Bolke and Sumsion, 1978). In contrast, other basins indicate an excess of recharge over discharges. Pine Valley and Wah Wah Valley have estimated discharges of 8.8 hm^3/yr and 1.8 hm^3/yr, respectively, by evapotranspiration, wells, and springs. These valleys have estimated recharge rates from precipitation of 25.9 hm^3/yr and 8.6 hm^3/yr, respectively (Stephens, 1976 and 1974, respectively).

A large part of the region is underlain by a thick sequence of carbonate rocks of Paleozoic age. It is inferred that the carbonate rocks act as a regional aquifer and subdrain the Bonneville region. Recharge to the carbonate aquifer is by infiltration of precipitation in the mountain ranges and downward flow from basin-fill deposits in areas such as Pine Valley and Wah Wah Valley. Discharge from the carbonate-rock aquifer is by upward flow to basin fill and then evapotranspiration from large areas of shallow ground water and by discharge to thermal springs in Fish Springs Flat, Tule Valley, southern Great Salt Lake Desert, and probably Snake Valley. A hypothetical regional potentiometric map for the deep carbonate rocks and contiguous rocks is shown in plate 3. The regional potentiometric surface in the carbonate rocks is inferred to be lower than the shallow water levels in the areas that contribute recharge to the carbonate rocks and higher than the water level at the springs and in the areas of discharge from the carbonate rocks. In spite of the uncertainties of the exact head in the carbonate and contiguous rocks, the shape of the water-level contours indicating direction of flow, the altitude of the water level relative to the basin fill, and the areas of discharge can be drawn with some confidence. However, the areal distribution of permeability is not known, and therefore, flow in the carbonate rocks and contiguous rocks at depth is not known. It is also evident, from both the water-level data in the basin fill and the water budgets for the basins in the Bonneville region and surrounding areas, that flow in the carbonate rocks extends beyond the Bonneville region. There appears to be underflow to the Bonneville region from the Sevier Desert, and the data strongly suggest the potential for underflow from basins to the west and southwest in Nevada. A summary of ground-water flow components integrating the water-level maps for the basin fill and carbonate aquifer, and estimates of recharge and discharge for the basins in the Bonneville region are given in table 1 and plate 2. The estimates of recharge by precipitation and discharge by wells, evapotranspiration, and springs are given as reported by Gates and Kruer (1981, their table 7) except as indicated in table 1. The estimates of subsurface inflow and outflow from the basins are inferred on the basis of flows necessary to balance the water-budget estimates of recharge and discharge for each basin. The assumed distribution of subsurface flow is consistent with the hypothetical water-level potential for the carbonate and contiguous rocks at depth.

In reviewing the evidence for interbasin flow in the region, Gates and Kruer (1981) pointed out the disparities in recharge and discharge discussed above and shown in the water budgets for the basins (table 1, pl. 3). Gates and Kruer suggested that the recharge to the Deep Creek Range could be one potential source for the Fish Springs group of springs. However, carbonate rocks are missing in the southern half of the Deep Creek Range and the part of the Deep Creek range most likely lying upgradient from the Fish Springs group of springs (pl. 3). The southern Deep Creek Range is underlain by intrusive igneous rocks and sedimentary and metasedimentary quartzites. There is an excess of ground water in the three basins, Deep Creek Valley, Tippett Valley, and Antelope Valley, of about 16 hm^3/yr. Some ground water may move by underflow into Snake Valley, but most probably moves to the Great Salt Lake Desert. The regional contours on the carbonate and contiguous rocks indicate underflow might move to Blue Lake Springs and nearby springs and to the Bonneville Salt Flats, which is a major discharge area within the Great Salt Lake Desert.

GROUND-WATER FLOW ANALYSIS

AREAL GROUND-WATER FLOW

Areal ground-water flow was analyzed in the basin-fill deposits and in the regional carbonate-rock aquifer. Relative ground-water traveltimes at the water table were analyzed using the procedure described in Chapter A (Bedinger and others, 1989). The relative velocities in the hydrogeologic units are shown in plate 4. Relative velocities are reported because site-specific data are not available for the region. The values of hydraulic properties of the units and hydraulic gradients used in estimating relative ground-water velocities are given in table 2.

The hydraulic gradients for the hydrogeologic units are representative gradients taken from the water-level contour map (Bedinger and others, 1984). The ratio of hydraulic conductivity to effective porosity was estimated using the values in Chapter A and modified as necessary during the verification of the cross-sectional and areal-flow models.

Ground-water traveltimes near the water table are shown in plate 5. Flow paths along which the relative traveltimes were calculated and major discharge areas, large springs, and evapotranspiration areas are also shown on the map. Flow at the water table in several basins is inferred to terminate by downward flow to the regional carbonate-rock aquifer. These areas are shown diagrammatically as diamonds in plate 5. The exact position of the downward flow is not known and may take place over a broad area in the closed basins. Traveltime in the deep aquifers was modeled for a selected geologic section using a separate digital model.

CROSS-SECTIONAL MODELS

Cross-sectional models were used to analyze ground-water flow along selected flow paths. The mathematical model used in modeling flow in geologic sections is

TABLE 1.—*Summary of ground-water flow components for the Bonneville region and vicinity, Utah and Nevada*
[All rates are in cubic hectometers per year (hm^3/yr)]

Hydrologic area	Recharge[1] by precipitation	Discharge[1]		Subsurface inflow	Subsurface outflow
		Evapotranspiration	Wells, seeps, and springs		
Dugway Valley–Government Creek area.	14.8	<1.2	3.5	Mower and Feltis (1968) estimated less than 6.2 hm^3/yr subsurface inflow from the Sevier Desert through alluvium. The boundary of the area as drawn on plate 3 probably includes the recharge area of this 6.2-hm^3/yr recharge. The hydraulic gradient in the deep carbonate or other consolidated rock indicates potential for flow from the Sevier Desert beneath the Dugway Valley–Government Creek area to the Great Salt Lake Desert.	Stephens and Sumsion (1978) estimated 9.9 hm^3/yr of subsurface outflow in the basin fill to the Great Salt Lake Desert in order to balance the water-budget equation for the area. There is a low gradient in underlying consolidated rock for subsurface outflow to the Great Salt Lake Desert.
Fish Springs Flat.	4.9	9.9	33.3	Subsurface inflow must be large to support the flow of Fish Springs because local recharge is only 4.9 hm^3/yr. Inflow must be as much as 38.2 hm^3/yr or more—some inflow probably continues to flow north to discharge to the Great Salt Lake Desert. Subsurface flow is probably from Snake, Pine, and Wah Wah Valleys by way of the Tule Valley and the Sevier Desert.	A small subsurface outflow in basin fill has been estimated by Bolke and Sumsion (1978). Additional outflow to the Great Salt Lake Desert may occur in the carbonate-rock aquifer.
Deep Creek Valley.	21	14.8	2.0	Excess of recharge over discharge in Antelope and Tippett Valleys west of Deep Creek Valley and hydraulic potential from the west indicate underflow of as much as 12.3 hm^3/yr or more.	The Gates and Kruer (1981) revision of the Deep Creek Valley surface outflow is about 3.7 hm^3/yr originating in Deep Creek Valley. Additional subsurface outflow originates from inflow from basins to the west of Deep Creek Valley. The hypothetical gradient of hydraulic head in the carbonate-rock aquifer indicates subsurface flow would be to northern Snake Valley and to the Great Salt Lake Desert. Carbonate rocks are missing in the southern Deep Creek Mountains on the southeastern margin of Deep Creek Valley, where the bedrock is Precambrian sedimentary and metasedimentary rock and Tertiary igneous intrusive rock—rocks very likely of lower hydraulic conductivity than the carbonate-rock aquifer.

TABLE 1.—*Summary of ground-water flow components for the Bonneville region and vicinity, Utah and Nevada*—Continued

Hydrologic area	Recharge[1] by precipitation	Discharge[1]		Subsurface inflow	Subsurface outflow
		Evapotranspiration	Wells, seeps, and springs		
Snake Valley	[6]130.7	[3,4]78.9	[4,7]12.3	The potential for subsurface inflow from the west is indicated by the hypothetical potentiometric surface in carbonate and contiguous rocks. Water budgets in adjacent valleys to the west, however, do not indicate an excess of ground water, and the gradient from the west is relatively low. Locally, along the western boundary, the carbonate rocks are not present in the section. Subsurface inflow to Snake Valley is evidently relatively small.	Hood and Rush (1965) estimated that about 12.33 hm³/yr is discharged by outflow in the basin fill to the Great Salt Desert. Outflow through the carbonate-rock aquifer is about 27.1 hm³/yr. However, outflow would be greater by the amount of subsurface inflow to Snake Valley from the west.
Tule Valley	9.4	39.5	<1	Discharge to springs, and by evapotranspiration in Tule Valley exceeds the local recharge. Inflow is indicated by excess ground water in adjacent valleys and hypothetical potential gradient in the carbonate-rock aquifer from the west and south. Inflows from Pine, Wah Wah, and Snake Valleys probably are as much as 51.8 hm³/yr subsurface inflow, and there probably is inflow from the Sevier Desert.	Fish Springs appears to be downgradient from Tule Valley through the carbonate rock aquifer. Part of the underflow from adjacent probably continues beneath Tule Valley to discharge at Fish Springs.
Wah Wah Valley.	8.6	<1	1.1	Subsurface inflow is indicated from the potentiometric surface in the carbonate-rock aquifer map (pl. 3) from Pine Valley and the Beryl-Enterprise and Milford areas to the south and east. Stephens (1974) estimated that 3.7 hm³/yr of recharge to Pine Valley was contributed as inflow. As much as 13.6 hm³/yr or more may originate in Pine Valley, based on the excess of recharge over discharge in Pine Valley.	Discharge from wells, springs, and by evapotranspiration in Wah Wah Valley is very small. Discharge of most of the recharge within the valley, which is from precipitation and underflow from the west, south, and east, is by underflow principally to the north. This outflow could be 24.7 hm³/yr (Gates and Kruer, 1981).
Pine Valley	25.9	6.8	2.0	The hypothetical gradient in the carbonate-rock aquifer indicates potential for inflow from the northern part of Snake Valley to the west.	The hypothetical gradient in the carbonate-rock aquifer indicates potential for outflow from Pine Valley (13.6 hm³/yr based on water-budget estimates) principally to Wah Wah Valley.
Tippett Valley	[5]8.5	[5]0	[2]<1	The hypothetical hydraulic gradient in the carbonate-rock aquifer indicates a potential for inflow from Steptoe Valley on the west.	Subsurface outflow, about 6.2 hm³/yr or more, is to the Great Salt Lake Desert beneath Deep Creek Valley and southern Antelope Valley.

TABLE 1.—*Summary of ground-water flow components for the Bonneville region and vicinity, Utah and Nevada*—Continued

Hydrologic area	Recharge[1] by precipitation	Discharge[1]		Subsurface inflow	Subsurface outflow
		Evapotranspiration	Wells, seeps, and springs		
Antelope Valley	[5]5.8	[5]<1	[2]2	Hydraulic potential exists for flow in carbonate or other consolidated rock into Antelope Valley from Steptoe Valley on the west. Water-budget studies for Steptoe Valley do not indicate a significant excess of recharge over discharge.	Antelope Valley probably loses water by subsurface outflow, about 6.2 hm³/yr, on the basis of water-budget studies. The hypothetical hydraulic gradient in the carbonate-rock aquifer indicates flow beneath Deep Creek Valley and the Great Salt Lake Desert.
Southern Great Salt Lake Desert.	58.0	77.7	25.9	The Southern Great Salt Lake Desert receives inflow from basins given in the table above and from other adjacent basins. Subsurface inflow occurs both in the basin fill and in consolidated rocks.	None.

[1]Recharge and discharge rates as revised by Gates and Kruer (1981, their table 7) except as indicated.
[2]Partial estimate.
[3]From Price (1979).
[4]Spring discharge included in evapotranspiraton estimate.
[5]From Harrill (1971).
[6]Modified from Gates and Kruer (1981), based on revision of basin boundary in present report.
[7]Estimated by J.S. Gates (U.S. Geological Survey, oral commun., 1984).

TABLE 2.—*Hydraulic properties of hydrogeologic units modeled in areal ground-water flow analysis*

[K, hydraulic conductivity, in meters per day; ϕ, effective porosity; ---, not estimated]

Hydrogeologic Unit	Map symbol (plate 4)	K/ϕ	Hydraulic gradient
Basin fill	a	6×10^{1}	0.005
Volcanic rocks, undifferentiated.	v	1×10^{-1}	0.02
Ash-flow tuff	t	1×10^{-1}	0.02
Fine-grained clastic rocks	f	3×10^{-9}	---
Carbonate rocks	c	1×10^{-1}	0.02
Metamorphic rocks	m	2×10^{-1}	0.02
Granitic rocks	g	2×10^{-1}	0.02

TABLE 3.—*Hydraulic properties of hydrogeologic units used in cross-sectional models*

[K, hydraulic conductivity, in meters per day; ϕ, effective porosity]

Hydrogeologic unit	Symbol on (plate 6)	*A–A'*	
		K	ϕ
Ash-flow tuff	T	4×10^{-4}	0.35
Carbonate rocks (dense to moderately dense).	c	3×10^{-3}	0.01
Carbonate rocks (fractured or karstic).	C	6×10^{0}	0.12
Coarse-grained basin fill	a	1×10^{0}	0.18
Crystalline rocks (lower part of section).	g	3×10^{-7}	0.04
Fine-grained basin fill	A	2×10^{-2}	0.32
Fine-grained clastic rocks	f	5×10^{-7}	0.22

given in Chapter A of this Professional Paper. The map location of the geologic section and the model parameters and results are shown in plate 6. The values of hydraulic properties of the rock units in the geologic section used in analysis of the ground-water flow are given in table 3.

Distribution of rock units, relative traveltimes, and stream functions are given on the cross-sectional model (pl. 6). Relative traveltimes are given in intervals of one order of magnitude from 10^1 and longer. Numbers indicate the relative time of travel from points on the line to the discharge area. Stream functions show the directions of ground-water movement, and the numbers indicate the relative amount of flow in the section below the flow line.

The cross-sectional model gives a more realistic concept of the traveltime between widely spaced points in the region than does the map of traveltime at the water table. As seen from the section, the flow paths in the divide areas of the flow system dive steeply into the flow system and take the longest flow paths to the discharge areas. Relative traveltimes from the divide areas to discharge areas are as great as 10^5 to 10^7. Commonly, these longest relative traveltimes are of restricted surface area at the water table. The areas of longer relative traveltime enlarge with depth and would provide more confidence in locating an area of long traveltime at depth beneath the water table than above the water table. Broad areas of relative traveltime of 10^5 or greater exist at the water table in the cross-sectional model.

QUALITY OF GROUND WATER

The quality of ground water in the Bonneville region is characterized by the areal distribution of dissolved solids (fig. 12) and predominant chemical constituents in solution (fig. 13). These maps are generalized from those of Thompson and Chappell (1984) and Thompson and Nuter (1984) that were compiled from the water-quality files of the U.S. Geological Survey (WATSTORE) and published reports. The data are mostly from nongeothermal springs and wells less than 150 m in depth and completed in alluvial and basin-fill deposits. In areas where data are not available, the water-quality parameters were estimated from the position in the ground-water flow system and the lithology of the local bedrock.

The concentration of dissolved solids is generally less than 500 mg/L. Dissolved solids increase near and in the major valleys adjoining the Great Salt Lake Desert in the northern part of the region. The greatest dissolved-solids concentration is in the Great Salt Lake Desert where the concentration is greater than 200,000 milligrams per liter.

The predominant chemical constituents in the ground water are calcium, magnesium, and sodium bicarbonate. Water of the sodium bicarbonate type is prevalent in the southern part of the region in association with the volcanic rocks. Water in which chloride is a principal cation is associated with the areas of higher dissolved-solids content.

PLEISTOCENE HYDROLOGIC CONDITIONS

The Pleistocene lakes in the Bonneville region accompanied the pluvial climates that existed during glacial stages of the Pleistocene. The glacial climates of the Pleistocene are believed to have been times of greater precipitation and lower temperature, (Snyder and Langbein, 1962; Mifflin and Wheat, 1979), although some investigators believe the greater water yield resulted solely from a decrease in temperature (Galloway, 1970; Brakenridge, 1978).

During the late Pleistocene, Lake Bonneville inundated an area of about 51,660 km^2 in the Basin and Range province (Williams and Bedinger, 1984), mostly in Utah but extending into Nevada. Lake Bonneville attained a maximum lake level of 1,550 m above sea level. At the maximum stage a surface drainage outlet developed northward through Red Rock Pass into the Snake River basin. The level of Lake Bonneville then receded to what is now called the Provo shoreline at an elevation of about 1,460 m. A wave-cut notch at the Provo level is shown in figure 14. In addition, a small lake, about 106 km^2 in area, is believed to have occupied Pine Valley.

Recurrence of climates that existed in the Pleistocene potentially would refill Lake Bonneville to the level of the Provo shoreline and increase the rate of recharge of ground water. Refilling of Bonneville to about 1,460 m would inundate the lower Snake Valley, Tule Valley, Fish Springs Flat, and Dugway Valley–Government Creek area. Inundation of the Sevier Desert would extend into the northern end of the Wah Wah Valley.

Inundation of a larger surface area would decrease the length of many flow paths at the water table to the discharge areas. Much of the flow in the carbonate rocks would tend to discharge in localized zones of high permeability, as it does now at springs. Ground water in the carbonate rocks, however, might find new spring openings such as beneath the lake in Wah Wah Valley and in the lake in Pine Valley.

Increased recharge would increase the hydraulic gradient to the discharge areas and decrease the depth to water. However, depth to water probably still would be greater than 150 m in many ranges.

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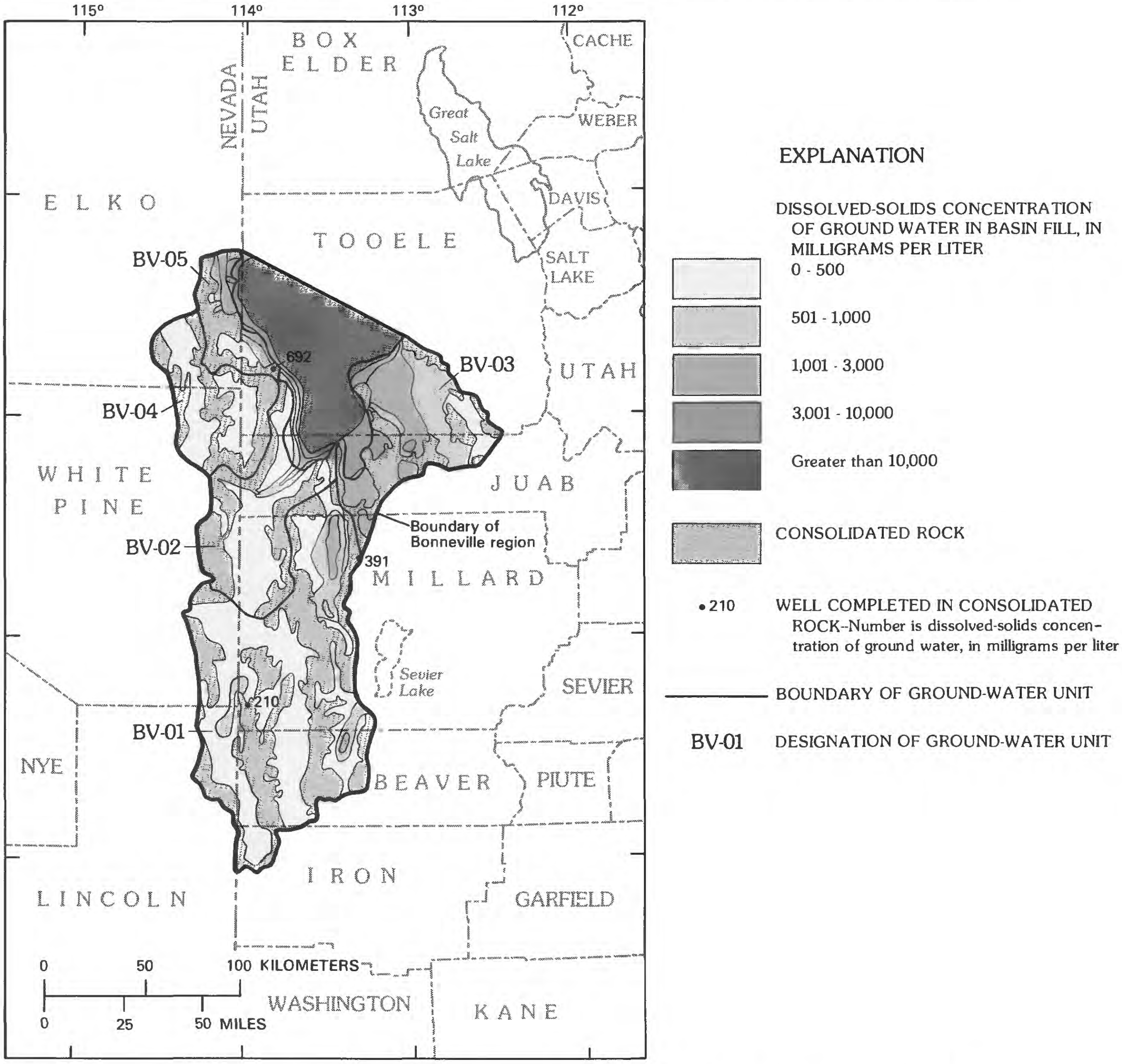

FIGURE 12.—Dissolved-solids concentration of ground water in the Bonneville region, Utah and Nevada.

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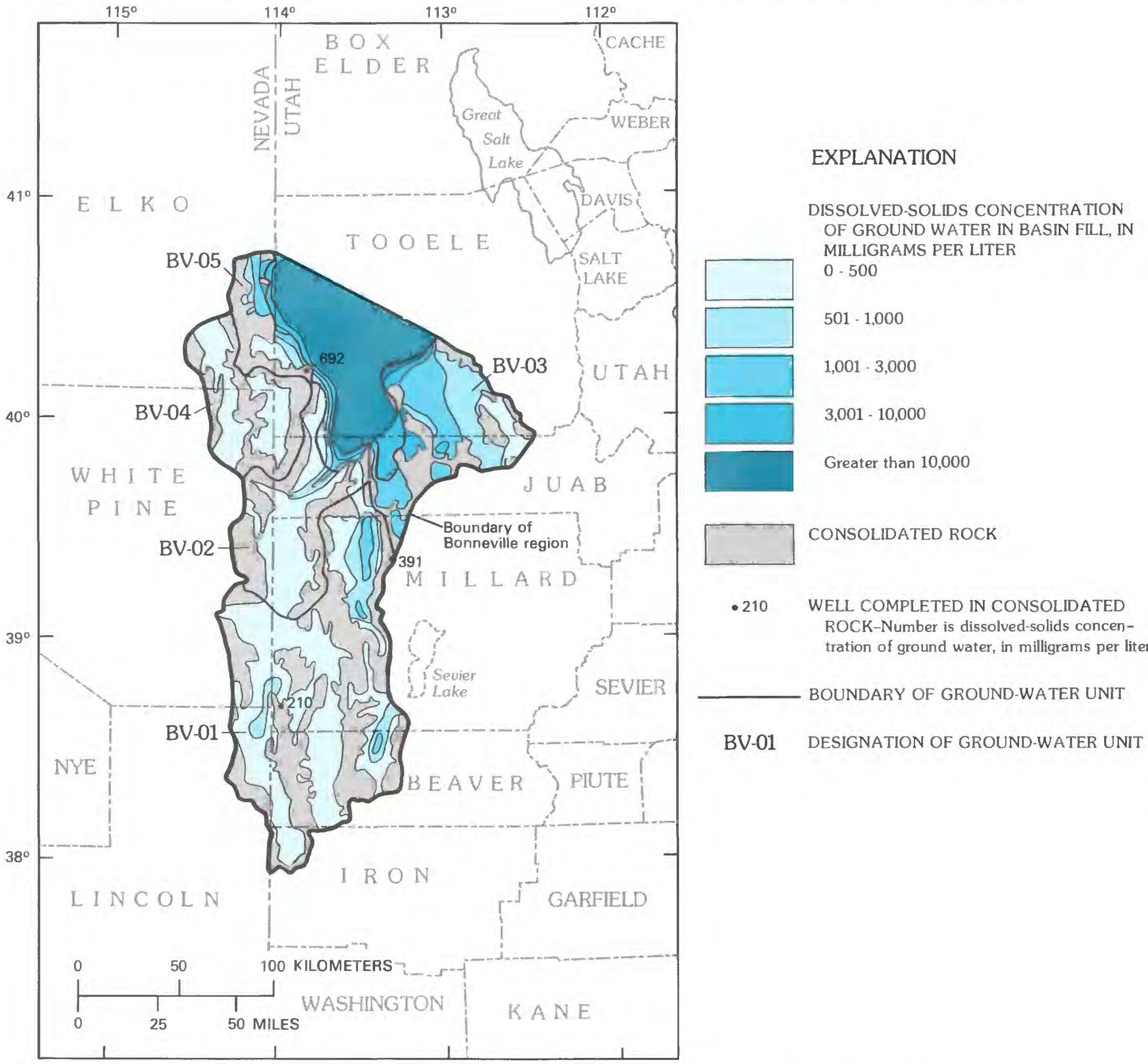

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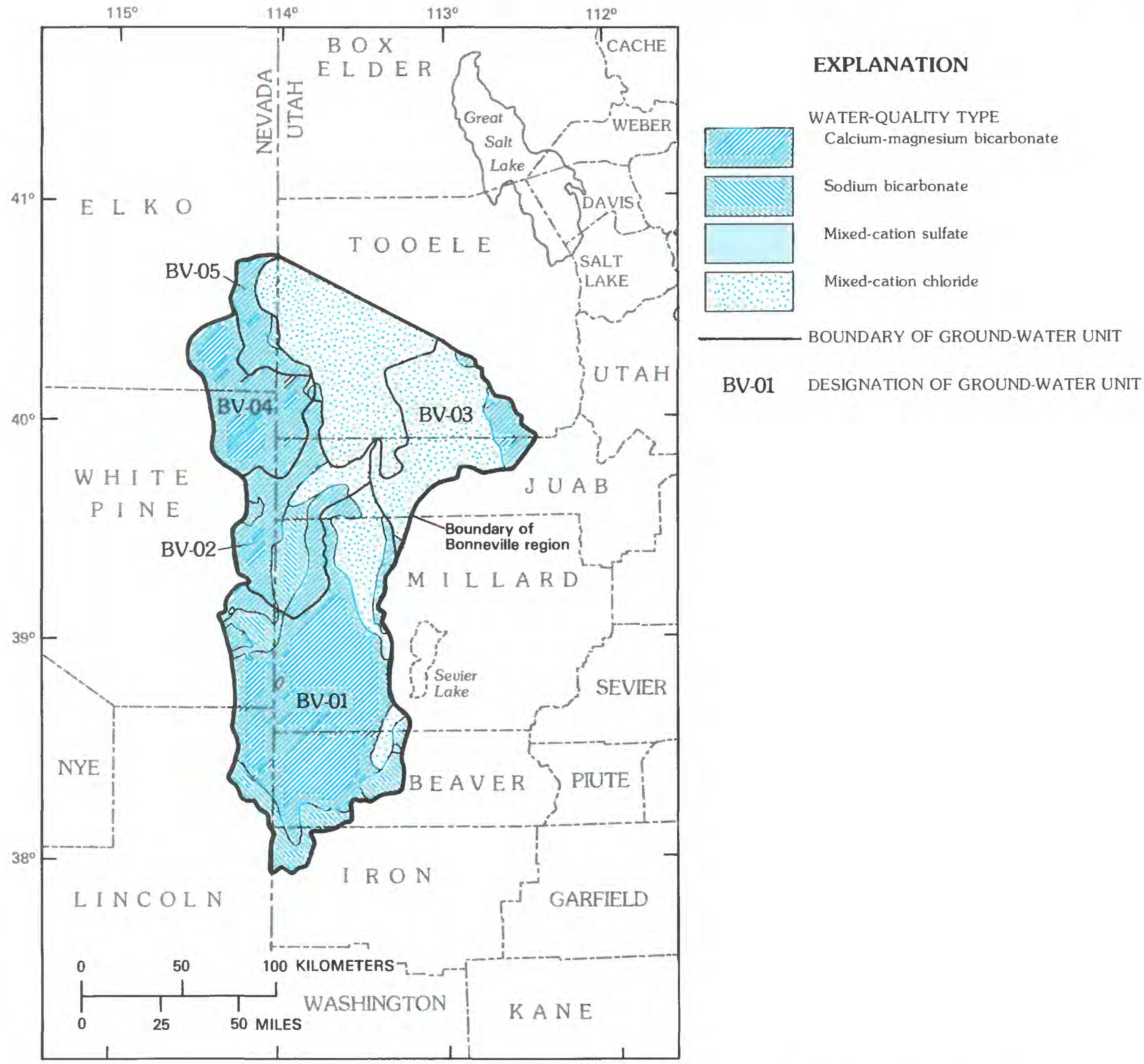

FIGURE 13.—Distribution of chemical types of ground water in the Bonneville Region, Utah and Nevada.

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FIGURE 14.—Photograph of wave-cut notch (arrow) at Provo level of Lake Bonneville in Tertiary volcanic rock hills south of Wendover, Elko County, Nevada. Photograph by K.A. Sargent (1984).

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MINERAL AND ENERGY RESOURCES

By B.T. Brady

There are at least 38 mining districts in the Bonneville region of Utah and Nevada. Beryllium-bearing ores at Spor Mountain (east of the Thomas Range), Juab County, and base- and precious-metal deposits in the San Francisco district, Beaver County, Utah, account for the bulk of the value of metals produced in the region to date. The Gold Hill district, Tooele County, and Fish Springs district, Juab County, Utah, and the Osceola district, White Pine County, Nev., have each produced concentrates worth a few millions of dollars. Gold is being produced presently in the Willow Springs district, Tooele County. Metallic mineral deposits in the Bonneville region are of two main types: vein and replacement deposits of Tertiary age. Fluorspar is the principal industrial mineral commodity with significant production. Locally important fluorspar mining has been primarily from breccia pipes. A few isolated, geothermal low-temperature springs and wells (water commonly less than 50 °C), are located in the Bonneville study area. A thin bed of radioactive lignite in the Heavenly Hills area, Juab County, constitutes the only presently known occurrence of coal. Several boreholes have reported shows of hydrocarbons; however, no wells have produced significant amounts of oil or gas to date.

METALLIC MINERAL RESOURCES

The resource areas in the Bonneville region are those areas delineated by Wong (1982, 1983), and their locations are shown on plate 7. These areas generally indicate the limit of productive workings. The resource areas of Wong are not all inclusive, and they do not indicate the extent of mineralized rock. The boundaries of the mineralized areas mentioned herein do not coincide with the limits of established metal-mining districts. These data were compiled primarily from the U.S. Geological Survey's Computerized Resource Information Bank (CRIB). The Utah Geological and Mineral Survey and Nevada Bureau of Mines and Geology currently maintain and revise this file in cooperation with the U.S. Geological Survey.

The majority of the mineral deposits in the Bonneville region are of Tertiary age. These areas of mineralization contain metal-bearing deposits that occur in diverse modes and lie within several east-northeast-trending belts of Cenozoic volcanic and intrusive rocks (Shawe and others, 1978). These areas of igneous activity and related mineralization are aligned along zones of pronounced structural weakness (Hilpert and Roberts, 1964; Shawe and Stewart, 1976).

Many of the mineral deposits in the Bonneville region contain base and precious metals in fracture-controlled epithermal veins or replacement deposits in carbonate rocks. A few of the mineralized areas contain ores in strataform, breccia pipes, or fissure deposits. The sites of the principal metal production and most extensive workings in the Bonneville region include the San Francisco and Preuss districts, Beaver County, Gold Hill district, Tooele County, and Spor Mountain and Fish Spring districts, Juab County, Utah, and the Osceola district, White Pine County, Nev. Table 4 contains a summary of the commodities and modes of occurrence for the principal mineral deposits in the Bonneville region.

Lead, silver, copper, gold, zinc, and beryllium are the principal metallic commodities with important production in the mining districts of the Bonneville region. Iron, tungsten, and molybdenum are elements that have been produced locally in smaller amounts. The San Francisco district in Beaver County, Utah, was a major source of base and precious metals in the study area. This district contains vein and disseminated deposits in Tertiary lavas, mineralized chimneys in intermediate intrusives, and contact- and fault-controlled replacement orebodies primarily in carbonate rocks of Paleozoic age (Butler, 1913). The bulk of the value and tonnage in areas mined in the San Francisco district came from the replacement and fissure vein deposits in the Horn Silver and Beaver Carbonate mines on the eastern flank of the San Francisco Range. Metals worth about $34 million were produced between 1879 and 1917 from mines in the San Francisco district and the adjacent Preuss district to the north (Butler and others, 1920).

The Gold Hill mining district, located at the northern end of the Deep Creek Range in Tooele County, Utah, contains numerous small vein and replacement deposits. Lead, zinc, copper, and silver were mined primarily from replacement orebodies in the Pennsylvanian Oquirrh Formation (Nolan, 1935). Copper-bearing veins are present in a quartz-monzonite stock. Lode-gold veins occur in limestone near the intrusive, and tungsten mineralization is present in irregular tactite zones peripheral to the stock. Furthermore, the Mississippian Ochre Mountain limestone contains notable amounts of arsenic in two limestone replacement bodies (Nolan, 1935). Recurrent episodes of faulting contributed significantly to the small size of many of the ore zones. Production in the Gold Hill district was mainly from lode-gold

TABLE 4.—*Resource areas of the Bonneville region of Utah and mineralized areas of the Bonneville region of Nevada, by county*

[Utah data from Wong (1983); Nevada data from Wong (1982). Commodities in the commodities column are abbreviated as follows: Ag, silver; Al, aluminum; As, arsenic; Au, gold; B, boron; Ba, barium; Be, beryllium; Bi, bismuth; Cu, copper; F, fluorine; Fe, iron; Hg, mercury; Li, lithium; Mg, magnesium; Mn, manganese; Mo, molybdenum; Pb, lead; S, sulfur; Sb, antimony; Sn, tin; Th, thorium; U, uranium; V, vanadium; W, tungsten; Zn, zinc. These data are preliminary and subject to revision]

Resource area/ mineralized area	Commodities	Deposit type	Host rock	References
Juab County, Utah				
Desert Mountain	Cu, Ba	Vein	Granite	Butler and others, 1920; Hillier, 1956.
Fish Springs	Ag, Au, Pb, Zn, Cu, Mo, Fe, Be, U, V, F, Mg.	Replacement	Notch Peak Formation	Bullock, 1976; Buranek, 1948; Butler and others, 1920; Crawford and Buranek, 1957; Heyl, 1963; Lindsey, 1977; Montoya and others, 1964; Oliveira, 1975; Perry and McCarthy, 1976; Staatz and Bauer, 1950; James, 1973.
		Bedded	White tuff	
		Vein	Bell Hill Member of Laketown Dolomite.	
Honey Comb Hills	U, F, Be	Disseminated	Tuff of Topaz Mountain Rhyolite.	Cadigan and Ketner, 1982; McAnulty and Levinson, 1964; Montoya and others, 1964; Staatz and Bauer, 1950.
Spor Mountain	F, U, V, Be, Li, Mg, Mn.	Pipe	Lost Sheep Member of Laketown Dolomite, Florida Member of Ely Springs Dolomite; Bell Hill Member of Laketown Dolomite, Fish Haven Dolomite.	Bauer, 1952; Bullock, 1976; Chojnack, 1964; Dasch, 1967; Leedom and Mitchell, 1978; Lindsey, 1977, 1979; Lindsey and others, 1973; Meeves, 1966.
		Vein	Lost Sheep Member of Laketown Dolomite, Rhyolite, Bell Hill Member of Laketown Dolomite.	Montoya and others, 1964; Shaw, 1968; Shaw and others, 1964; Staatz, 1963; Staatz and
		Bedded	Tuff member of Spor Mountain Formation.	Bauer, 1950; Staatz and Carr, 1964; Staatz and Griffitts, 1961; Staatz and Osterwald, 1959; Thurston and others, 1954.
Spring Creek	Pb, Zn, W, F, Be.	Veins	Muscovite-bearing quartz veins in dolomite of Precambrian Trout Creek sequence.	Everett, 1961; Thomson, 1973.
	Pb, Zn, W, F, Ag, Au, Cu, Fe, U, Mn, Be.	Veins	Trout Creek sequence, Johnson Pass sequence.	Butler and others, 1920; Everett, 1961; Heyl, 1963; Thomson, 1973.
		Gossan	Chainman Shale	
Topaz Mountain	U, F	Vein	Tuff	Leedom and Mitchell, 1978; Outerbridge and others, 1960; Staatz and Carr, 1964.
Trout Creek	U	Radioactive lignite	Tertiary gravels	Thomson, 1973.
	Fe	Gossan	Limestone of Pennsylvanian Ely Formation.	
	Cu, Fe, Mn	Veins	Quartz veins in schist of Precambrian Johnson Pass sequence.	Thomson, 1973.

TABLE 4.—*Resource areas of the Bonneville region of Utah and mineralized areas of the Bonneville region of Nevada, by county*—Continued

Resource area/ mineralized area	Commodities	Deposit type	Host rock	References
Millard County, Utah				
Gordon	F, S	Replacement	Callvile Limestone	Bullock, 1976; Davis, 1949.
Tooele County, Utah				
Columbia	Ag, Pb, Zn	Vein	Quartzite	Bullock, 1970; Butler and others, 1920; Cohenour, 1959; Heyl, 1963.
Dugway	Ag, Au, Pb, Zn, Cu, Fe, F.	Replacement Vein	Dolomite, limestone Quartzite	Bullock, 1976; Butler and others, 1920; Heyl, 1963; Perry and McCarthy, 1976; Staatz and Carr, 1964.
Erickson	Ag, Au, Pb, Zn, Cu, Mn, U, F.	Replacement	Quartzite	Bullock, 1976; Butler and others; 1920; Cohenour, 1959; Crittenden, 1951; Heyl, 1963; Hillier, 1956; Pardee, 1922.
Gold Hill	Ag, Au, Pb, Zn, Cu, Fe, Mo, W, Bi, V, Be, Ba, As, F, B.	Vein Contact metamorphic Replacement Gossan Pegmatite	Quartz monzonite, Oquirrh Formation, Ochre Mountain Limestone. Ochre Mountain Limestone Oquirrh Formation Ochre Mountain Limestone Quartz monzonite	Bullock, 1970, 1976; Buranek, 1948; Butler and others, 1920; Custer, 1917; Nolan, 1935. El-Shatoury and Whelan, 1970; Everett, 1961; Foshag and others, 1930; Garvin, 1966; Griffitts, 1965; Heyl, 1963; Kemp and Billingsley, 1918; Lemmon, 1964; Lemon and Tweto, 1962; Meeves, 1966; Nolan 1935; Perry and McCarthy, 1976; Schaller and Nolan, 1931; Thomson, 1973.
Granite Peak	Ag, Pb, Cu, Fe, Be, F, mica.	Vein Pegmatite	Granite Biotite granite gneiss.	Bullock, 1967; Butler and others, 1920; Elevatorski, 1974; Fowkes, 1964; Hanley and others, 1950.
Willow Springs	Ag, Au, Pb, Zn, Cu, Fe, Hg, Ba, Sb.	Replacement Vein	Dolomite, quartzite Quartzite, dolomite, limestone.	Hilpert, 1964; Nolan, 1935; Perry and McCarthy, 1976; Thomson, 1973.
Beaver County, Utah				
Blawn Mountain	Fe, Alunite, kaolinite, F, U, Sn.	Replacement Fissure filling Altered silicified breccia. Replacement Breccia	Paleozoic carbonate rocks do. Oligocene rhyolite Brecciated intrusive topaz rhyolite. Rhyolite	Bullock, 1970. Parkinson, 1974; Thurston and others, 1954; Whelan, 1965. Lindsey and Osmonson, 1978; Whelan, 1965. Lindsey and Osmonson, 1978.
Washington	F, U, Cu	Vein Vein	Porphyritic ignimbrite Wah Wah Springs Tuff Member of Needles Range Formation.	Bullock, 1976; Everett, 1961; Frey, 1947; Thurston others, 1954; Everett and Wilson, 1950.

TABLE 4.—*Resource areas of the Bonneville region of Utah and mineralized areas of the Bonneville region of Nevada, by county*—Continued

Resource area/ mineralized area	Commodities	Deposit type	Host rock	References
Beaver County, Utah—Continued				
Pine Grove	Ag, Au, Pb, Zn, Cu, Fe, Mo, U, Sn, Be, Mn, F, Al, clay.	Gossan Vein Replacement Fracture filling	Undifferentiated limestone do. Pioche Shale, limestone Prospect Mountain quartzite	Bullock, 1970, 1976; Crittenden, 1951; Heyl, 1963; Jones and Dunham, 1946; Miller, 1966; Perry and McCarthy, 1976; Taylor and Powers, 1959; Thurston and others, 1954; Whelan, 1965.
Wah Wah Pass	Fe, Mn	Replacement Fissure fillings Pipelike bodies	Cambrian limestone of the Orr and Weeks Formations. Hematite in fault gouge Adjacent to contact between diorite or quartz-diorite dikes and Paleozoic carbonate rocks.	Bullock, 1970.
Preuss	Ag, Au, Pb, Cu, Ba, Fe.	Disseminated Breccia pipe Vein Replacement	Cactus quartz monzonite do. Prospect Mountain quartzite Limestone	Butler, 1913; Emmons, 1902; Lindgren, 1910; Perry and McCarthy, 1976.
San Francisco	Ag, Au, Pb, Zn, Cu, Fe, W, Mo, F.	Contact metasomatic Replacement Fissure filling Skarn	Limestone of Orr Formation do. Volcanic rocks, quartz monzonite Limestone	Bullock, 1976; Butler, 1913; Butler and others, 1920; East, 1966; Emmons, 1902; Everett, 1961; Hobbs, 1945; Koschman and Bergendahl, 1968; Lemmon and Tweto, 1962; McKelvey, 1973; Perry and McCarthy, 1976; Stringham, 1967; James, 1973.
Iron County, Utah				
Indian Peak	Ag, Au, Pb, Zn, Cu.	Contact metasomatic	Dolomite	Heyl, 1963.
Stateline	Ag, Au, Cu, Pb, Mn.	Vein	Welded tuff	Butler and others, 1920; Koschman and Bergendahl, 1968; Thomson, 1973.
Elko County, Nevada				
Dolly Varden	Au, Ag, Cu, Pb, Zn, Mo, Th.	Contact metamorphic Replacement Vein	Limestone, quartz monzonite Limestone Quartz monzonite	Granger and others, 1957; Hill, 1916; Lincoln, 1923; Smith, 1976.
Ferber	Au, Ag, Cu, Pb.	Vein Porphyry copper	Quartz monzonite do.	Granger and others, 1957; Hill, 1916; Lincoln, 1923; Smith, 1976.
Ferguson Spring	Au, Ag, Cu, Pb.	Replacement	Limestone	Granger and others, 1957; Hill, 1916; Lincoln, 1923.
Kinsley	Au, Ag, Cu, Pb, W, Mo.	Contact metamorphic Replacement Vein	Limestone, quartz monzonite Limestone Dolomite	Emmons, 1910; Granger and others, 1957; Lincoln, 1923; Matson, 1947.
Wendover	W	Unknown	Unknown	Smith 1976.
White Horse	Ag, Pb, Zn, Cu, W.	Vein	Quartz monzonite	Granger and others, 1957; Hill, 1916; Lincoln, 1923; Smith, 1976.

TABLE 4.—*Resource areas of the Bonneville region of Utah and mineralized areas of the Bonneville region of Nevada, by county*—Continued

Resource area/ mineralized area	Commodities	Deposit type	Host rock	References
White Pine County, Nevada				
Black Horse	Au, Ag, Pb, Cu, W, Zn.	Vein Pods Placer	Limestone, shale Conglomerate Gravel	Hose and others, 1976; Lemmon and Tweto, 1962.
Lexington	W	Vein Placer	Limestone Alluvium	Hose and others, 1976; Lincoln, 1923.
Lincoln	W, Be, Pb, Ag, Cu, Sb.	Vein Replacement	Limestone do.	Hose and others, 1976; Stager, 1960; Whitebread and Lee, 1961.
Mount Moriah	Au, Ag, Pb, Zn, Cu, W, Garnet.	Placer garnet Replacement Contact	Creek bed Limestone Limestone, intrusives	Hose and others, 1976.
Osceola	Au, Ag, Pb, Zn, Cu, W.	Vein Placer	Quartzite, granite porphyry Gravel	Hose and others, 1976; Lincoln, 1923; Weeks, 1908.
Red Hills	Pb, Ag, Cu, Au.	Breccia zone	Limestone	Hill, 1916; Hose and others, 1976.
Snake	Ag, Pb, Cu, W.	Vein	Quartz monzonite	Hose and others, 1976
Tungstonia	Pb, Ag, Au, Cu, W, Zn, Bi, F.	Vein Replacement	Limestone, granite Brecciated limestone	Couch and Carpenter, 1943; Hill, 1916; Hose and others, 1976; Lincoln, 1923.

deposits. Gold, silver, copper, lead, and zinc ores worth at least $2 million were mined between 1901 and 1927, and approximately 4,536 Mg of metallic arsenic were shipped from 1920 to 1925 (Nolan, 1935).

Gold is currently being mined by the Evelyn Limited Partnership in Goshute Canyon in the Willow Springs district. Lode gold and associated base-metal sulfides occur along an extensive silicified fracture system in the Cambrian Prospect Mountain Quartzite (Thomson, 1973). Approximately 20,000 oz of gold were produced previously from this property (Bryce Tripp, Utah Geological and Mineral Survey, written commun., 1984).

Several mineralized areas occur along pronounced east-trending vein systems in the northern part of the Fish Springs Range, Juab County, Utah. The productive zones are composed of small, irregular replacement bodies in Ordovician and Silurian carbonate rocks, commonly near the footwall of granite-porphyry dikes (Butler and others, 1920). Lead and silver ores were the primary sources of production in the Fish Springs district. The gold content of the mineralized zones is low, and copper occurs chiefly in secondary minerals in the oxidized zone (Butler and others, 1920). Approximately 2.5 million oz of silver and more than 7,258 Mg of lead were mined between 1891 and 1917, and the cumulative value of metals produced in the Fish Springs district exceeds $2.3 million (Butler and others, 1920).

Numerous thin gold- and silver-bearing quartz veins occur in quartzite in the Osceola district, White Pine County, Nev. These lodes and several nearby placer deposits were worked continuously from 1901 to 1959 (Smith, 1976). Precious metals in the lodes and placers accounted for the principal value of metal production in the district. Small amounts of lead, zinc, and copper also were produced from the vein deposits. Approximately 550 short tons of tungsten were mined from a pipelike replacement body in the Wheeler Formation and from a scheelite-bearing quartz vein that cuts the Cambrian Prospect Mountain Quartzite (Smith, 1976). The tungsten deposits occur commonly near a Mesozoic(?) granitic intrusive or metadolerite dike. The combined production of metals from mines in the Osceola area was estimated to exceed $3.3 million (Smith, 1976).

The Spor Mountain district is located in Juab County, Utah, about 80 km northeast of Delta. Beryllium is economically the most important metal in the district; however, productive fluospar and uranium mines also are located in the area. The Yellow Chief mine immediately east of the district contains an estimated 90,720 Mg of uranium ore with a grade of at least 0.2 percent

U_3O_8 (Bowyer, 1963; Hewitt, 1968). Extensive bertrandite-bearing ore zones with minor associated phenakite occur in thick sections of Pliocene water-laid tuff of the Spor Mountain Formation that were deposited in a lacustrine environment (Shawe, 1968). The 6–7-m.y.-old tuff of the Topaz Mountain Rhyolite contains less extensive zones of beryllium mineralization (Lindsey, 1981). Principal zones of beryllium mineralization are restricted to hydrothermally altered horizons containing altered clasts of Paleozoic dolomite. The Spor Mountain district contains one of the largest known nonpegmatitic resources of lowgrade beryllium ore in the world (Griffitts, 1964). Several million metric tons of beryllium ore with at least 0.5 percent Be0 are identified in the district (Shawe, 1968).

The majority of the presently known occurrences of iron in the Bonneville region are located in Beaver County, Utah. These deposits are commonly irregular, concordant replacement bodies near the contact between Paleozoic limestones and local intrusives. Less than 1.8 million Mg of combined production and resources are estimated to occur at each locality (Reeves, 1964).

Several scattered occurrences of tungsten and molybdenum have been noted in the study area (Hobbs, 1945; Lemmon, 1964; King, 1964), and these areas have produced little ore to date.

NONMETALLIC AND INDUSTRIAL MINERAL RESOURCES

Nonmetallic industrial minerals and rocks occur throughout the Bonneville region. Excluding natural aggregates and building stone, nonmetallic industrial minerals and rocks have been mined on a small scale primarily for local use. Fluorspar is the principal industrial mineral commodity mined to date in the study area. A small amount of barite has also been produced in two localities.

The Spor Mountain district, Juab County, Utah, contains the principal productive fluorspar mines in the Bonneville region. Between 1944 and 1975 more than 204,120 Mg of fluorspar were mined, principally from breccia pipes (Bullock, 1976). In addition, mines in the Washington district, Beaver County, Utah, have produced at least 18,144 Mg of metallurgical-grade fluorspar (Bullock, 1976).

A few thousand Mg of barite were produced in western Utah between 1955 and 1961 under a federally subsidized incentive program (Brobst, 1964). The bulk of the production was from the Garrick mine in the Fish Springs district, Juab County, Utah, and the Horn Silver mine in the San Francisco district, Beaver County, Utah, contributed the remainder of the ore (Brobst, 1964; Elevatorski, 1974).

GEOTHERMAL RESOURCES

There are relatively few geothermal occurrences in the Bonneville region. Geothermal springs are located in the Snake Valley and Tule Valley, west-central Millard County, and near the northern end of the Fish Springs Range in western Juab County, Utah. Wilson's Health Spring near the northern end of the Fish Springs Range has a temperature of 61 °C, and this is the warmest geothermal spring in the study area (Murphy, 1980). The remaining geothermal springs in the Bonneville region of Utah have temperatures generally between 20 and 30 °C. The Kern Mountains Spring and Big Spring in eastern White Pine County, Nev., are the only geothermal occurrences identified presently in the Bonneville region of Nevada. These springs contain warm water with temperatures less than 37 °C (Garside and Schilling, 1979). No geothermal wells with temperatures in excess of 50 °C occur presently in the Bonneville region of Nevada (Garside and Schilling, 1979; Murphy, 1980). Furthermore, no lands in the Bonneville region are currently classified as Known Geothermal Resource Areas (U.S. Bureau of Land Management, 1983a, 1983b).

COAL, OIL, AND GAS RESOURCES

No major coal occurrences are known in the Bonneville region (Doelling, 1982; Schilling, 1980). A thin bed of radioactive lignite has been prospected by a 7.6-m-deep incline in the Heavenly Hills area, western Juab County, Utah. The lignite reportedly contains from 0.01 to 0.31 percent uranium (Thomson, 1973). More than 20 hydrocarbon exploration boreholes have been drilled in the study area (Brady, 1983). Shows of oil or gas have been observed in some of these holes; however, no production has been reported to date. There are currently no Known Geologic Structures in the Bonneville region (U.S. Bureau of Land Management, 1983a, 1983b).

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