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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1370–F

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

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

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CONVERSION FACTORS

For use of readers who prefer to use U.S. customary units, conversion factors for terms used in this report 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	
hectare (ha)	2.471	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
	Velocity	
meter per day (m/d)	3.281	foot per day (ft/d)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
	Flow	
liter per minute (L/min)	0.2642	gallon per minute (gal/min)
	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 DEATH VALLEY REGION, NEVADA AND CALIFORNIA

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

ABSTRACT

The Death Valley region, Nevada and California, in the Basin and Range province, is an area of about 80,200 square kilometers located in southern Nevada and southeastern California. The linear mountains and valleys of the region have a distinct northwest trend, reflecting the late Cenozoic structural grain. The valleys are closed topographic basins, except for an area that drains to the Colorado River. The region ranges in altitude from 86 meters below sea level at Death Valley, the lowest point in the United States, to about 3,600 meters above sea level. Relief between valleys and adjoining mountains only locally exceeds 1,500 meters.

Precambrian metamorphic and intrusive basement rocks are overlain by a thick section of Paleozoic clastic and evaporitic sedimentary rocks. Mesozoic and Cenozoic rocks include extrusive and intrusive rocks and clastic sedimentary rocks. Structural features within the Death Valley indicate a long and complex tectonic evolution from late Precambrian to the present. Potential repository host media in the region include granite and other coarse-grained plutonic rocks, ash-flow tuff, basaltic and andesitic lava flows, and basin fill. Thick unsaturated zones in the region contain potential repository media. Evidence of Quaternary tectonic conditions in the region include seismic activity, faulting, volcanic activity, and vertical crustal movement. Geothermal heat flow ranges from less than 1.5 to about 2.5 heat-flow units.

The Death Valley region is composed largely of closed topographic basins that are apparently coincident with closed ground-water flow systems. In these systems, recharge occurs sparingly at higher altitudes by infiltration of precipitation or by infiltration of ephemeral runoff. Discharge occurs largely by spring flow and by evaporation and transpiration in the playas. Death Valley proper, for which the region was named, is the ultimate discharge area for a large, complex system of ground-water aquifers that occupy the northeastern part of the region. The deepest part of the system consists of carbonate aquifers that connect closed topographic basins at depth. The discharge from the system occurs in several intermediate areas that are geomorphically, stratigraphically, and structurally controlled. Ultimately, most ground-water flow terminates by discharge to Death Valley; ground water is discharged to the Colorado River from a small part of the region.

The region contains metallic mineral deposits in diverse geologic environments. The mineralized areas commonly contain precious-metal deposits and base metals in replacement deposits.

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, and others, 1989). The evaluation of the region 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 closely 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 Death Valley region, Nevada and California, Chapter F, is one of six reports characterizing the geology and hydrology of regions in the Basin and Range province. Chapter F 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 this report was prepared under the general guidelines established 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 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. In parts of the region, inadequate data exists to characterize these areas. In these places it was necessary to discuss the geologic or hydrologic characteristics in the vicinity of the region, and then project that data into these areas.

GEOGRAPHIC SETTING

The Death Valley region, Nevada and California, is an area of about 80,200 km^2, located in southern Nevada and southeastern California (pl. 1). The linear mountains and valleys of the region have a distinct northwest trend, reflecting the late Cenozoic structural grain. The valleys are closed topographic basins, except parts of ground-water unit DV-01 which drain to the Colorado River. The region ranges in altitude from 86 m below sea level at Death Valley to 3,600 m above sea level. The topography generally rises northward, although there are some high mountains in the southwestern part of the region; for example, Telescope Peak overlooks Death Valley, from an altitude of about 3,370 m. The mountains in the northern part of the region commonly range in altitude from 2,500 to 3,000 m, whereas those in the southern part are slightly lower, commonly with altitudes ranging from 1,800 to 2,500 m. Relief between the valleys and adjoining mountains only locally exceeds 1,500 m.

Most of the basins in the region seldom contain standing water. Playas or dry lake beds and alluvial flats constitute about 10 percent of the region.

An aerial photograph of the dry lake bed of Racetrack Playa in a small closed basin north of Death Valley is shown in figure 1. The remaining area is about equally divided between mountains and gravel fans.

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 given following the title page. Susan L. Tingley of Nevada, alternate member of the Province Working Group, contributed significantly to the regional phase of the study. The following individuals provided continued advice and assistance to the Basin and Range 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 assistance in preparation of the

FIGURE 1.—Southward view of the Racetrack, the dry playa of a small (about 175 km^2) topographically closed basin northwest of Death Valley. The playa is about 4 km long from north to south and has a maximum width of about 2 km. Photograph by John S. Shelton (1979).

ground-water section of this report of the following colleagues of the U.S. Geological Survey who generously provided information and interpretive judgments used in this section: Isaac J. Winograd, James R. Harrill, W.R. Moyle, Alan H. Welch, and James R. Thomas.

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GEOLOGY

By T.L.T. GROSE[1] and GEORGE I. SMITH

EARLY AND MIDDLE PROTEROZOIC CRYSTALLINE BASEMENT ROCKS

The oldest rocks in the Death Valley region constitute an Early Proterozoic quartzofeldspathic-augen-gneiss basement complex. Exposures, widely scattered in the southern one-half of the region, occur in the Panamint Range (Hunt and Mabey, 1966; Labotka and others, 1980a, b), Black Mountains area (Drewes, 1963; Wright and Troxel, 1983), Clark Mountain Range (Burchfiel and Davis, 1971; Olson and others, 1954), McCullough Range (Bingler and Bonham, 1973; Hewett, 1956), and Eldorado and Newberry Mountains (Volborth, 1973). Geographic features referred to in this report are shown in figure 2.

In the southern part of the Death Valley region (Panamint Range and Black Mountains), the crystalline basement is composed of granitic and quartz-monzonitic augen gneiss with inclusions of biotite-quartz schist and lesser porphyritic granite, amphibolite, quartzite, and pegmatite. Oldest ages are 1.82–1.79 b.y. (Stern and others, 1966); pegmatites are 1.73–1.66 b.y. old and granites are about 1.35 b.y. old (Lanphere and others, 1963; Wasserburg and others, 1959). In the Clark Mountain Range area, the basement consists of a complex of granitic gneiss, biotite-garnet-sillimanite gneiss, and amphibolite gneiss, variously intruded by granite, syenite, and carbonatite. Granitic gneiss is dated at 1.7 ± 0.065 b.y.and carbonatites at 1.4 b.y. (Lanphere, 1964). In southernmost Nevada, in the McCullough Range and Eldorado and Newberry Mountains, a high-grade complex of paragneiss, schist, marble, amphibolite, migmatite and pegmatite, about 1.7 b.y. old, is intruded by rapakivi granite about 1.45 b.y. old (Stewart, 1980, p. 9, 12).

Two small outcrops in southern Nye County, Nev., distant from the areas described above, consist of metamorphic rocks of questionable Proterozoic age. Muscovite-biotite gneiss and schist invaded by irregular masses of coarse-grained gneissic granite occur in the Bullfrog Hills area (Cornwall and Kleinhampl, 1964). Gneissic quartz monzonite and biotite-amphibole schist crop out in the Trappman Hills (Ekren and others, 1971). These metamorphic rocks have not been radiometrically dated, thus the possibility remains that they may be metamorphosed Paleozoic rocks and, therefore, unrelated to the Proterozoic crystalline basement exposed many kilometers to the west and south.

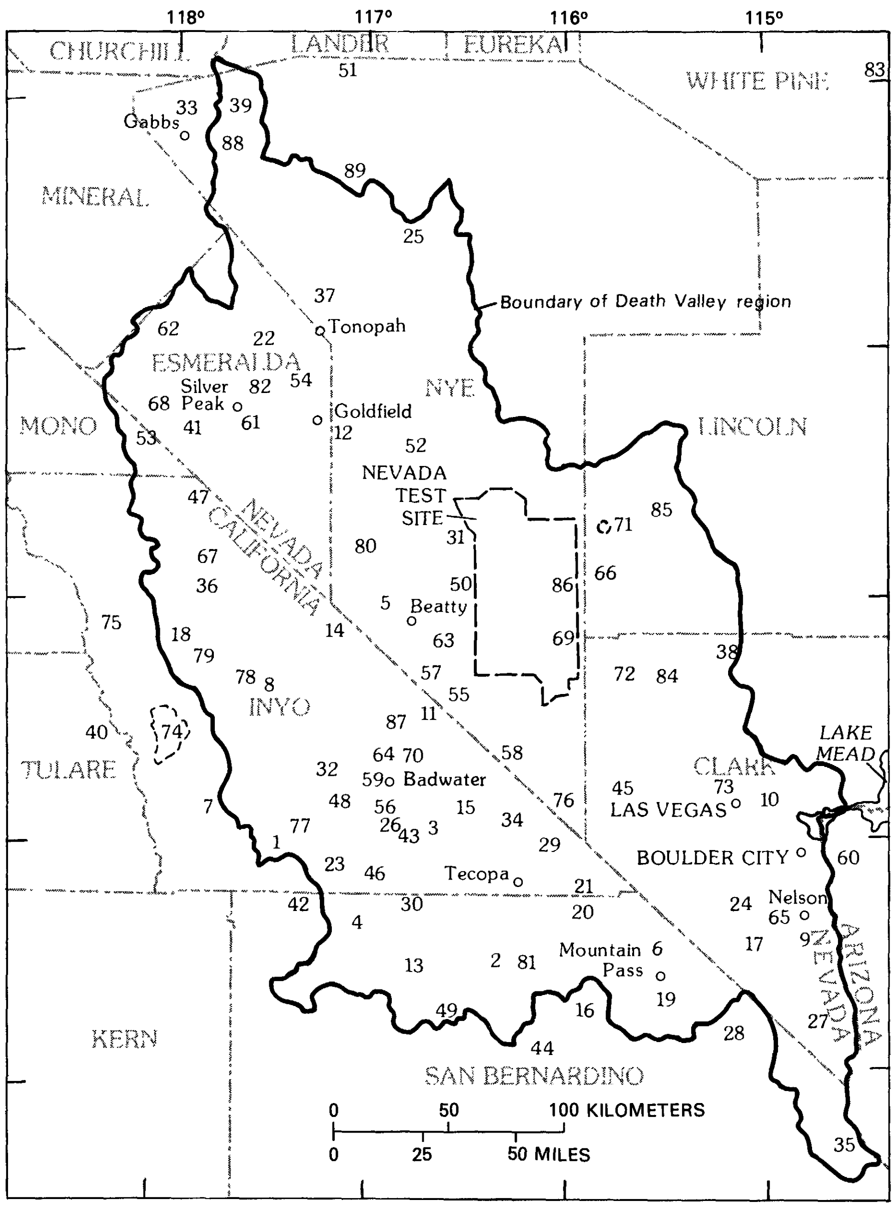
[1]Nevada Bureau of Mines and Geology and Colorado School of Mines.

The Proterozoic crystalline rocks form a continuous basement, but one that has been tectonically thickened and thinned as well as extensively intruded by plutons and caldera complexes. The top of the basement occurs at disparate altitudes. It is probable that the central and southeastern parts of the Death Valley region are underlain by Proterozoic granitic basement. The northwestern part may have a thinned or discontinuous (rifted) Proterozoic basement complex, or it may have none (Kistler, 1974; Stewart, 1980, p. 9–11). Toward the west, most Proterozoic basement rocks probably have been incorporated into Mesozoic plutonic bodies (Wright and others, 1981).

MIDDLE AND LATE PROTEROZOIC SEDIMENTARY ROCKS

In a relatively small area of the southern Death Valley region, the Panamint Range and Black Mountains–Kingston Peak area, a distinct sequence of sedimentary rocks is preserved resting unconformably on Proterozoic crystalline basement. This sequence, called the Pahrump Group, locally attains a thickness of 2 km. It is divided into a lower Crystal Spring Formation composed of arkose, siltstone, shale, and dolomite; a middle Beck Spring Dolomite; and a thick, upper Kingston Peak Formation composed of sandstone, conglomerate, and diamictite, as well as debris eroded from basement rocks, the Crystal Spring Formation, and the Beck Spring Dolomite (Labotka and Albee, 1977; Troxel, 1967; Wright and others, 1976, 1981). Extensive diabase sills occur within the Crystal Spring Formation, and in the Panamint Range basalt flows (some with pillows) locally appear within the Kingston Peak Formation. The Pahrump Group is everywhere complexly deformed, locally metamorphosed mainly in the Panamint Range, and widely intruded by Mesozoic and Cenozoic plutons. Marked lithologic heterogeneity and facies relationships show that the Pahrump strata were deposited in fault-controlled basins with local uplands as sediment-source areas. As a composite sequence, Pahrump strata fill what has been termed the Amargosa aulacogen, a northwest-trending rift with well-preserved northeastern-margin faults, but with poorly documented southwestern-margin structure (Wright and others, 1976).

The Pahrump Group lies unconformably on basement plutons in the Panamint Range dated at 1.35–1.4 b.y., and it is overlain unconformably by Late Proterozoic unfossiliferous sedimentary rock 1,000–2,000 m thick in continuous succession beneath Early Cambrian



EXPLANATION

1 ARGUS RANGE
2 AVAWATZ RANGE
3 BLACK MOUNTAINS
4 BROWN MOUNTAIN
5 BULLFROG HILLS
6 CLARK MOUNTAIN RANGE
7 COSO RANGE
8 COTTONWOOD MOUNTAINS
9 ELDORADO MOUNTAINS
10 FRENCHMAN MOUNTAIN
11 FUNERAL MOUNTAINS
12 GOLDFIELD HILLS
13 GRANITE MOUNTAINS
14 GRAPEVINE MOUNTAINS
15 GREENWATER RANGE
16 HALLORAN HILLS
17 HIGHLAND RANGE
18 INYO MOUNTAINS
19 IVANPAH MOUNTAINS
20 KINGSTON PEAK
21 KINGSTON RANGE
22 LONE MOUNTAIN
23 MANLY PEAK
24 MCCULLOUGH RANGE
25 MONITOR RANGE
26 MORMON POINT
27 NEWBERRY MOUNTAINS
28 NEW YORK MOUNTAINS
29 NOPAH RANGE
30 OWLSHEAD MOUNTAINS
31 PAHUTE MESA
32 PANAMINT RANGE
33 PARADISE RANGE
34 RESTING SPRINGS RANGE
35 SACRAMENTO MOUNTAINS
36 SALINE RANGE
37 SAN ANTONIO MOUNTAINS
38 SHEEP RANGE
39 SHERMAN PEAK
40 SIERRA NEVADA
41 SILVER PEAK RANGE
42 SLATE RANGE
43 SMITH MOUNTAIN
44 SODA MOUNTAINS
45 SPRING MOUNTAINS
46 SUGARLOAF PEAK
47 SYLVANIA MOUNTAINS
48 TELESCOPE PEAK
49 TIEFORT MOUNTAINS
50 TIMBER MOUNTAIN
51 TOIYABE RANGE
52 TRAPMAN HILLS
53 WHITE MOUNTAINS
54 ALKALI SPRINGS
55 AMARGOSA DESERT
56 AMARGOSA RIVER VALLEY
57 AMARGOSA VALLEY
58 ASH MEADOWS
59 BADWATER
60 BLACK CANYON
61 CLAYTON VALLEY
62 COLUMBUS SALT MARSH
63 CRATER FLAT
64 DEATH VALLEY
65 ELDORADO VALLEY
66 EMIGRANT VALLEY
67 EUREKA VALLEY
68 FISH LAKE VALLEY
69 FRENCHMAN FLAT
70 FURNACE CREEK WASH
71 GROOM LAKE
72 INDIAN SPRING VALLEY
73 LAS VEGAS VALLEY
74 OWENS LAKE
75 OWENS VALLEY
76 PAHRUMP VALLEY
77 PANAMINT VALLEY
78 RACETRACK PLAYA
79 SALINE VALLEY
80 SARCOBATUS FLAT
81 SILURIAN LAKE
82 SILVER PEAK MARSH
83 SPRING VALLEY
84 THREE LAKES VALLEY
85 TIKABOO VALLEY
86 YUCCA FLAT
87 FURNACE CREEK RANCH
88 GABBS DISTRICT
89 ROUND MOUNTAIN-MANHATTAN DISTRICT

FIGURE 2.—Geographic features of the Death Valley region and vicinity, Nevada and California.

fossil horizons. Therefore, the age of the Pahrump Group is between about 1.3 and 0.7 b.y.

LATEST PROTEROZOIC AND LOWER CAMBRIAN CLASTIC ROCKS

A westward-thickening miogeoclinal wedge of clastic rocks was deposited during latest Proterozoic and Early Cambrian time throughout the entire Death Valley region (Stewart, 1970; Stewart and Suczek, 1977). The rocks lie unconformably on a smooth surface of the Proterozoic crystalline basement, except in the southern Death Valley region where they lie with angular unconformity on the Pahrump Group. The thinnest section, less than 150 m thick, is composed of the Tapeats Sandstone and overlying Bright Angel Shale, which in this region occur only southeast of Las Vegas. To the northwest and west, the clastic wedge thickens by addition of older formations to a maximum of about 3,300 m in the Nopah and Resting Spring Ranges (Hazzard, 1937; Stewart, 1980; Stewart and Poole, 1975; Wright and others, 1981).

The wedge as a lithostratigraphic entity has been divided laterally into a quartzite and siltstone province in the central and eastern part of the Death Valley region, and into a siltstone, carbonate, and quartzite province in the western part (Stewart and Poole, 1975). The quartzite and siltstone province consists of the following formations in upward succession: Johnnie Formation, Stirling Quartzite, Wood Canyon Formation, Zabriskie Quartzite, and the lower one-half of the Carrara Formation. The Prospect Mountain Quartzite in southwestern Lincoln County, and the Dunderberg Shale and the Gold Hill Formation in northwestern Nye County, Nev., are included in the quartzite and siltstone province. The Noonday Dolomite, beneath the Johnnie Formation, is 500 m thick in the Panamint Range–Black Mountains area (Williams and others, 1976) and is 2,000 m thick in the Telescope Peak area of the Panamint Range (Albee and others, 1981). Cambrian guide fossils make their first appearance in the unbroken sedimentary section in the Wood Canyon Formation. The section thins southeastward from about 3,000 m in the western Spring Mountains (Burchfield and others, 1974) to zero in southernmost Nevada by erosional disconformities along a persistent shelf-craton hinge line. The section also thins westward from 3,300 m in the Nopah Range to about 2,500 m in the Panamint Range (Hunt and Mabey, 1966; Wright and others, 1981). The quartzite and siltstone province generally consists of "***fine- to medium-grained quartzite and sand units from 25 m to 1,200 m thick, separated by units of siltstone and very fine to fine-grained quartzite from 15 m to 300 m thick***" (Stewart, 1980, p. 14). Limestone, dolomite, and conglomerate are rare.

The siltstone, carbonate, and quartzite province includes the following formations in upward succession: Proterozoic Wyman Formation, Reed Dolomite, and Deep Spring Formation; Proterozoic and Cambrian Campito Formation; and Cambrian Poleta and Harkless Formations. These rocks, which occur in the western and northwestern parts of the Death Valley region (mainly Inyo County in California and Esmeralda County in Nevada), are thicker than those of the quartzite and siltstone province, exceeding 4,000 m in total thickness in the northern Inyo Mountains. Correlations between stratigraphic units of the two provinces were provided by Stewart (1970). The rocks are mainly shallow-water siltstone, carbonate rocks, and fine-grained quartzite deposited at the shelf margin and on the upper slope. They are less well preserved and less understood than their equivalents in the quartzite and siltstone province, because they have been more complexly deformed (mostly allochthonous), more generally regionally metamorphosed, and more subjected to plutonic intrusions (Stewart, 1970; Albers and Stewart, 1972).

MIDDLE CAMBRIAN THROUGH PERMIAN CARBONATE AND CLASTIC ROCKS

In continuous shelf deposition with the underlying clastic wedge, a thick miogeoclinal sequence of carbonate strata were deposited rather continuously from Middle Cambrian through Permian time throughout the central and eastern parts of the Death Valley region. During the same time, the western and especially the northwestern parts of the region received clastic and minor volcanic detritus in a complexly changing oceanic environment, interleaved with shelf-slope limestone and dolomite. Thicknesses of the Middle Cambrian through Permian section generally increase in a northwesterly direction from about 1,000 m in the southeastern to more than 8,000 m in the central part of the region. From the central part to the west and north, thicknesses remain great, but are less known due to structural complexities and lithologic variations (Burchfiel and Davis, 1981; Hunt and Mabey, 1966; McAllister, 1956; Nelson, 1966a, b, 1971; Stewart, 1980).

The thick and relatively uniform carbonate section is, as a whole, para-autochthonous in the central part of the region, although it has been tectonically transported several tens of kilometers eastward on several regional overthrust faults associated with the Cretaceous Sevier orogeny. The clastic and minor volcanic components are largely allochthonous and associated with: (1) The Roberts Mountains thrust of the Devonian-Mississippian Antler orogeny, which produced distinct clastic wedges derived from erosion of the Antler highland that intertongue with carbonate strata in the central part of the region; (2) local rift-basin deposition of Pennsylvanian Humboldt disturbance; and (3) the Golconda thrust of the Permian-Triassic Sonoma orogeny.

In the western part of the region, Paleozoic rocks younger than Middle Cambrian also developed coarse-clastic facies during the last one-third of Paleozoic time and possibly for related reasons, though this is not well established. Interbedded clastic facies first occur in rocks beginning with those of Permian age in the Panamint Range (Hunt and Mabey, 1966), and with those of Late Mississippian age in the northern Panamint Range and southern Inyo Mountains to the northwest (McAllister, 1956; Merriam, 1963); they first occur even earlier in the eugeosynclinal facies of Ordovician age in the northern Inyo Mountains (Nelson, 1966a). The clastic facies include siltstone, sandstone, and, in rocks younger than Mississippian, conglomerate. Some conglomerate facies appear to be intraformational, indicating that crustal deformation in areas to the northwest(?) had begun before the close of Mississippian time.

Numerous formational designations apply to the many distinctive lithologic units included within this long and thick stratigraphic interval. Only some major formations can be mentioned here. Middle and Upper Cambrian carbonate rocks occur in the upper one-half of the Carrara Formation and in the Bonanza King, and Nopah Formations (Palmer, 1971; Stewart and Suczek, 1977); shale and limestone occur in the Preble and Emigrant Formations. The Ordovician consists, in ascending order, of the Pogonip Group (limestone and minor shale), Eureka Quartzite, and Ely Springs Dolomite on the shelf province, and Palmetto Formation (shale, chert, quartzite) in the deep-water environment in the northwestern part of the region (Ross, 1977). Silurian and Devonian formations include Hidden Valley Dolomite, rocks formerly designated Nevada Formation (now obsolete), Lost Burro Formation, and Devils Gate Limestone (McAllister, 1956; Poole and others, 1977; Stewart, 1980). Mississippian strata include the Monte Cristo Limestone in the shelf-carbonate province, which is in the southeastern part of the Death Valley region; the Eleana Formation, a flysch and molasse sequence deposited in the central part of the region and derived from the Antler orogenic highland in the northwestern part of the region; and the Tin Mountain Limestone and Perdido Formation in the coarsening western facies (Poole and Sandberg, 1977; McAllister, 1956). Pennsylvanian and Permian strata are composed of the Tippipah, Bird Spring, Callville, Kaibab Limestones, Hermit Shale and Coconino Sandstone in the central and southern part of the region. The Pablo and Diablo Formations indicate a complex siliceous and volcanic province of Mississippian, Pennsylvanian, and Permian age in the northwestern part of the Death Valley region; the Rest Spring Shale and Keeler Canyon and Owens Valley Formations constitute a comparable assemblage in the western part of the region (Merriam, 1963; Albers and Stewart, 1972; Rich, 1977; Stevens, 1977; Stewart, 1980).

TRIASSIC AND JURASSIC SEDIMENTARY AND VOLCANIC ROCKS

Triassic and Jurassic layered rocks occur in the far northwestern and western parts, and in the far southeastern part of the Death Valley region. In southernmost Nevada and adjacent California, marine and continental deposits include the Moenkopi Formation of sandstone, shale, and minor limestone; the Chinle Formation of sandstone, siltstone, and shale; and the Aztec Sandstone. All rest uncomformably on Paleozoic rocks (Longwell and others, 1965; Wright and others, 1981). Possibly correlative facies of the Soda Mountains Formation, exposed just south of the Death Valley hydrologic unit, indicate an increasing volume of Mesozoic volcanic rocks in that direction (Grose, 1959). Total thickness in these areas is about 2,000 m.

Distinctly more complex and thicker accumulations occur in the western and northwestern parts of the region. In the southern Panamint Range, 2,500 m of metamorphosed clastic rocks and andesitic flows compose the section. About 50 km to the northwest, in the southern Inyo Mountains, 550 m of Triassic marine sedimentary rocks, composed of limestone and shale, rest unconformably on Permian strata and grade upward into more than 1,800 m of Triassic and Jurassic(?) volcanic flows and terrestrial conglomerate (Merriam, 1963; Dunne and others, 1978).

In northern Esmeralda and northwestern Nye Counties, Nev., the following formations occur in generally ascending order, but also in partial intertonguing or facies relationships: Candelaria Formation of shale, sandstone, conglomerate, and volcanic breccia; Excelsior Formation of greenstone breccia, tuff, and chert; the Luning, Gabbs, and Sunrise Formations of shale, sandstone, conglomerate, and carbonate; and the Dunlap Formation of conglomerate, sandstone, and minor limestone, and volcanic rocks (Stewart, 1980). These units generally are tightly folded and thrust faulted, variously metamorphosed, and locally intruded by plutons. These variable sedimentary and volcanic sequences reflect complexly and rapidly changing environments in a continuously active zone of the Sonoma and Nevadan orogenies (Burchfiel and Davis, 1981; Speed, 1978a, b).

CRETACEOUS THROUGH MIDDLE EOCENE SEDIMENTARY ROCKS

Rocks of this period, other than plutonic intrusives, are rare in the Death Valley region. Conglomerate and minor sandstone, termed "Older Clastic Rocks" by Tschanz and Pampeyan (1970), as much as 1,500 m thick, occur in the southwestern corner of Lincoln County, Nev. (Tschanz and Pampeyan, 1970); they are of questionable Cretaceous and early Tertiary age. Also, two small areas in northwestern Nye County preserve Cretaceous(?) and early Tertiary(?) clastic rocks (Stewart, 1980). It is likely that some of the deeper basins in Nevada may contain more deposits of this age, but the Death Valley region, as a whole, appears to have been a highland throughout that period, undergoing erosion and only locally accumulating continental clastic deposits in restricted basins.

UPPER EOCENE TO HOLOCENE SEDIMENTARY AND VOLCANIC ROCKS

Cenozoic layered rocks underlie most of the surface area of the Death Valley region, mainly in the basins, but also in the uplands and ranges. Some of the considerable variety of continental sedimentary rocks and unconsolidated deposits are free of volcanic debris of contemporaneous origin, although most of these rocks are tuffaceous and interstratified with volcanic sequences. Older sedimentary and volcanic rocks accumulated in large basins unrelated to presently preserved and active basins; younger deposits occur largely in modern basins.

In the Nevada part of the Death Valley region, Stewart (1980) and Stewart and Carlson (1976) have divided Cenozoic layered rocks into four general ages: (1) 43–34 m.y. (older than 34 m.y. for sedimentary rocks); (2) 34–17 m.y.; (3) 17–6 m.y.; and (4) younger than 6 m.y. These divisions also may apply to the California part, although a comparable study has not been made southwest of the Nevada border.

In the oldest age group, late Eocene and early Oligocene, the Titus Canyon Formation, about 500 m of conglomerate, sandstone, shale, tuff, and limestone, is exposed in small areas in southern Nye County of Nevada and Inyo County of California. Small areas of andesite flows and breccias occur in northwestern Nye County (Stewart, 1980).

In the 34–17-m.y.-age range, Oligocene and early Miocene, sedimentary rocks consist mainly of thin lenticular tuffaceous clastics within thick volcanic sections, some within calderas, occurring in a few localities in central and northern Nye County, Nev. (Stewart, 1980). In the Black Mountains–Funeral Mountains area (Hunt and Mabey, 1966), more than 1,000 m of conglomerate, sandstone, and minor shale and limestone, that are possibly of this age, are preserved. Widespread welded and non-welded silicic ash-flow tuffs, locally nearly 1,000 m thick, and minor andesitic and rhyolitic flows occur in northern Esmeralda County and in central and northwestern Nye County, Nev.

The period 17–6 m.y. ago, middle and late Miocene, is marked by two major changes: (1) Sedimentation, in part, took place in basins formed by basin-and-range faulting of modern configuration; and (2) widespread eruption of basaltic magma and bimodal suites of rhyolite and basalt began (Christiansen and Lipman, 1972; McKee, 1971). Conglomerate, sandstone, shale, limestone, and local diatomite compose fluvial and lacustrine sequences that are locally as much as 3,000 m thick and contain differing quantities of contemporaneous volcanic material. Many local formation names have been used for these rocks. In Esmeralda County and northwestern and southern Nye County, Nev., these tuffaceous sedimentary rocks are incorporated in part of the several-thousand-meter-thick Esmeralda Formation; in southwestern Lincoln County and western Clark County, Nev., they compose major parts of the Horse Spring Formation, Muddy Creek Formation, and others. In eastern Inyo County, Calif., more than 1,000 m of siliceous and intermediate volcanic rocks and interbedded clastic sedimentary rocks of this age, part of the Artist Drive Formation, are overlain by 2,000 m of conglomerate and sandstone of the Furnace Creek Formation in the northern part of the Black Mountains (Hunt and Mabey, 1966; McAllister, 1970); in the Panamint Range they are overlain by conglomerate and megabreccia of the "Nova Formation" of Hopper (1947) (Fanglomerate No. 3 of Hall, 1971) and all equivalent beds beneath the present basin floors. Relatively thin sedimentary layers occur within widespread volcanic sequences and caldera fills in the northern part of the Death Valley region.

The igneous rocks that range in age from 17–6 m.y. in the Death Valley region include as much as 1,000 m of basalt and andesite flows in northern Esmeralda County, and northwestern Nye County, Nev.; extensive silicic ash-flow tuffs, rhyolite flows, and andesite flows and breccias in Esmeralda County and southern Nye County, Nev., and adjacent areas in California; and basalt, andesite, dacite, and rhyolite flows and tuffs in southern Clark County, Nev. Prominent, in the scattered and diversified volcanic sequences of the eastern Death Valley region, is the concentration of calderas in southern Nye County, which are the sources of widespread ash-flow tuffs and associated rhyolite and related rocks. This particular area has been thoroughly mapped and many formations have been delineated and described extensively in the literature (Christiansen and others, 1977; Ekren and others, 1971; Stewart, 1980). In California, igneous rocks of these indicated ages include a granite batholith in the Kingston Range, a small area in the Argus Range (age questionable), several flows in the White Mountains (Luedke and Smith, 1981), and the oldest flows in the Cima volcanic field in northeastern San Bernardino County (Dohrenwend and others, 1984).

In the youngest age range, 6 m.y. to present, are latest Miocene, Pliocene, and Quaternary sedimentary rocks and unconsolidated deposits that underlie nearly one-half of the Death Valley region, and basaltic and minor andesitic flows that occur in about one percent of the area. Sedimentary material consists of coarse fanglomerate at the range fronts grading basinward through coarse to fine alluvium, sandstone, and siltstone, to claystone and locally limestone and evaporites in the lowest areas of deposition. In several scattered areas, eolian sand dunes and blankets occur, and gravel and sand beach and bar deposits represent shores of extensive Quaternary lakes. Consolidated and unconsolidated sediments younger than 6 m.y. are confined to modern basins, where they commonly exceed 500 m and may reach thicknesses of a few thousand meters.

Igneous activity, 6 m.y. and younger, consists of many widely scattered, mostly small basaltic cones and flows, and local maar deposits. Sedimentary sections of this age range usually do not contain appreciable volumes of tuffs or flows, in contrast to older sections. Basaltic eruptive centers occur at seemingly random locations in southern Esmeralda and southern Nye Counties in Nevada and in eastern Inyo and eastern Mono, and northeastern San Bernardino Counties in California.

MESOZOIC AND CENOZOIC PLUTONIC ROCKS

Plutonic rocks underlie many areas in the Death Valley region (Carlson and others, 1975; Jennings, 1961; Jennings and others, 1962; Stewart, 1980; Strand, 1967; Streitz and Stinson, 1974). In northwestern Nye County, Nev., a large Cretaceous pluton crops out in the southern part of the Toiyabe Range (Round Mountain-Manhattan district) and smaller bodies of Jurassic to Tertiary age crop out in the Gabbs district of the Paradise Range (Stewart and Carlson, 1978). In adjacent Esmeralda County, Nev., are many plutonic rocks that range in age from Triassic to Tertiary (Albers and Stewart, 1972; Stewart, 1980). The largest is the Palmetto Wash–Sylvania pluton of Jurassic age that underlies the southern part of the Silver Peak Range and parts of the Sylvania Mountains and Slate Range. Other plutons are the eastern part of the Cretaceous Inyo batholith in the White Mountains and the Lone Mountain–Weepah plutons and satellites in the Lone Mountain area. In southern Nye County, along the northern and northwestern margin of Yucca Flat, are two small Cretaceous granitic stocks (Cornwall, 1972), and elsewhere in the general region are several shallow plutonic or subvolcanic silicic intrusive masses that range in age from 6–34 m.y. (Stewart, 1980). In southern Clark County, Nev., there are three relatively large Miocene intrusions in the Eldorado and Newberry Mountains (Anderson and others, 1972).

In the California part of the Death Valley region, Triassic to Neogene plutonic rocks also occur in many areas. The large Jurassic Hunter Mountain pluton dominates the southwestern part of the Cottonwood Mountains, and most of the southern Argus Range is composed of plutonic rocks that can be considered the eastern edge of the Sierra Nevada batholith. Smaller bodies of Jurassic to Tertiary age crop out in the Panamint Range (the Tertiary Little Chief stock and the Mesozoic Hall Canyon and Manly Peak plutons), the Black Mountains, and the Greenwater Range. Farther south, large and irregularly outcropping masses of plutonic rocks occur widely in the Owlshead Mountains, Granite Mountains, Tiefort Mountains, Soda Mountains, Kingston Range (Tertiary), Halloran Hills, Ivanpah Mountains, and New York Mountains (Jennings, 1961; Jennings and others, 1962; Streitz and Stinson, 1974).

Most of the plutonic rocks of the Death Valley region are fine- to coarse-grained equigranular to porphyritic granodiorite and quartz monzonite. Alaskite, granite, diorite, gabbro, and rhyolite porphyry also occur in subordinate associated phases. In general, the plutonic rocks in the western part of the region are older, Triassic to Cretaceous, and similar petrographically and temporally to the mesozonal Sierra Nevada batholithic rocks (Burchfiel and Davis, 1981; Crowder and others, 1973; Evernden and Kistler, 1970). Farther east, the intrusive bodies are less abundant, smaller, and mostly Cretaceous and Tertiary. They are mostly epizonal and locally subvolcanic relative to caldera complexes, especially in Nye County, Nev. (Stewart, 1980, p. 112).

STRUCTURAL AND TECTONIC FEATURES

Structural features within the Death Valley region reveal a long complex tectonic evolution from late Precambrian to the present. No part of the region has escaped significant deformation and some parts have been nearly continuously active tectonically. Literature on the subject is voluminous; integrative, comprehensive, and summary papers are few. Perhaps the paper by Burchfiel and Davis (1981), which deals mainly with the California part, and that by Stewart (1980), which deals with the Nevada part of the Death Valley region, are the most concise, comprehensive, and up-to-date.

This brief summary will review the tectonic evolution mainly from a descriptive viewpoint beginning with the earliest record in the late Precambrian and following on through successively younger deformational events to modern time. Major structures in the Death Valley region are shown on a simplified tectonic map (fig. 3).

Four selected geologic sections through the Death Valley region and supportive data are shown on plate 2. Many other geologic sections similar to these have been systematically constructed through the Death Valley region as a major part of our regional studies.

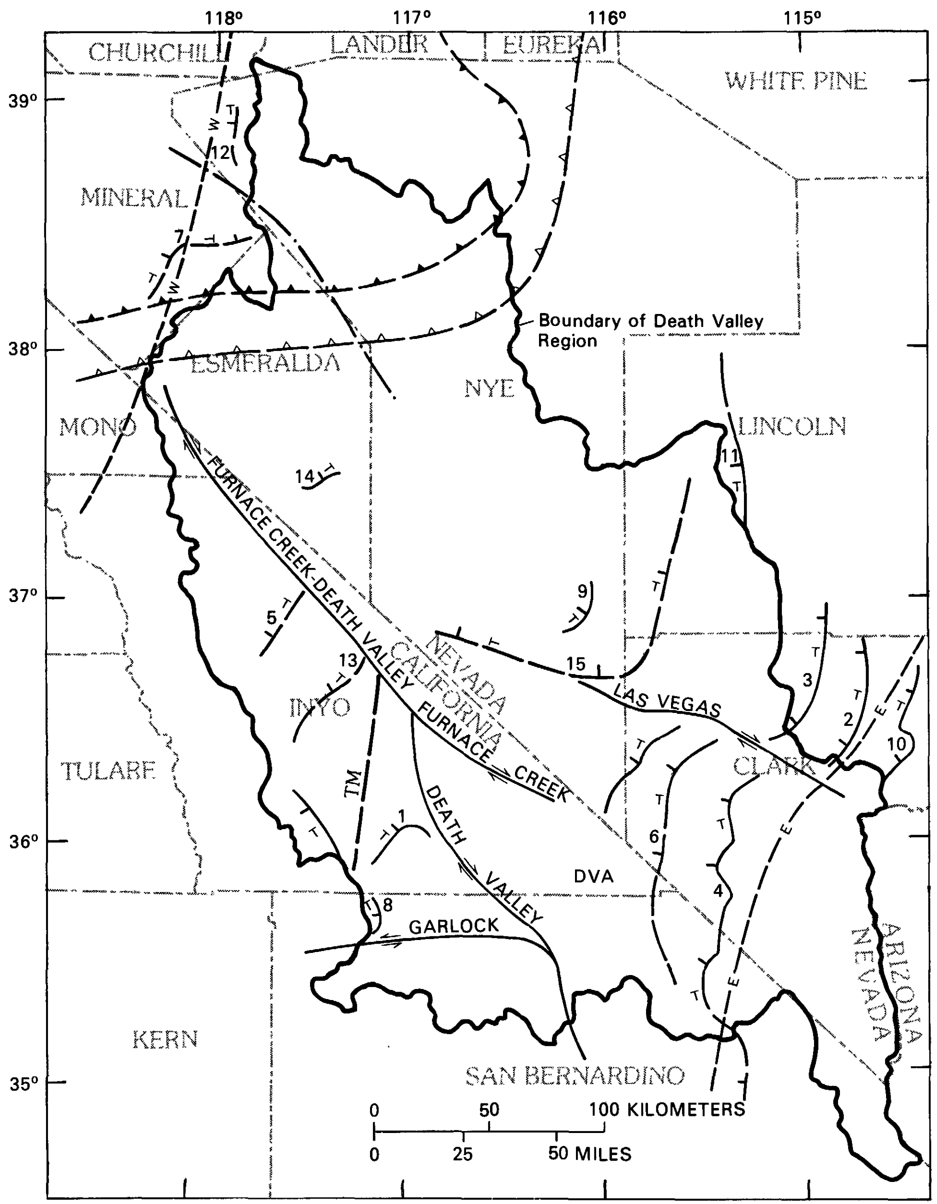
Precambrian metamorphic basement rocks, sparsely exposed, indicate a geosynclinal, orogenic, and magmatic arc terrane that composed part of the northeast-trending Transcontinental arch and was originally deformed during the interval 1,700–1,740 m.y. ago (Silver and others, 1977). The deposition of the Pahrump Group during late Precambrian time in fault depressions in southeastern Inyo County, Calif. (Wright and others, 1976) indicates continental-margin rifting. From late Precambrian to Devonian time, a time of relative tectonic quiescence, the Death Valley region composed part of a westward-thickening clastic and carbonate wedge of miogeoclinal shelf deposits, which is characteristic of a rifted and passive continental margin (Burchfiel and Davis, 1971; Dickinson, 1977; Stewart and Poole, 1975; Stewart and Suczek, 1977).

The first major Phanerozoic tectonic event in the Death Valley region was the Antler orogeny in the Late Devonian and Mississippian (Dickinson, 1977; Merriam and Anderson, 1942; Roberts and others, 1958), as is evident by the Roberts Mountain imbricate thrust complex that occurs in the northwestern part of the region (fig. 3) and also by a thick wedge of clastic rocks (Eleana Formation) derived from the Antler highland and deposited in a foredeep basin (Poole, 1974) that trends northeasterly through the central part of the region. During the Antler orogeny, eastward thrusting of more than 100 km brought deep ocean shale, chert, and minor volcanic rocks of the Roberts Mountain allochthon up and over shelf and transitional deposits of similar age to the east (obduction). The leading edge of the Roberts Mountain thrust is poorly located within the Death Valley region (Stewart, 1980, p. 38) as it veers westward from a northerly trend.

During the Carboniferous, after the Antler orogeny and before the Sonoma orogeny, rifting and some compression that affected the northern and western marginal areas of the Death Valley region apparently occurred—a deformational event that was called the Humboldt orogeny by Ketner (1977). Local basins with variable sedimentary rocks, some locally derived within the Antler highland, and other direct and inferred regional relationships (Burchfiel and Davis, 1975; Rich, 1977; Speed, 1977; Stevens, 1977; and Stewart, 1980) indicate that the Antler orogeny was interrupted by rifting and that an ocean basin expanded along the western margin of the continent in late Paleozoic time.

The Sonoma orogeny, Late Permian and Early Triassic, was similar to the Antler orogeny in that deep-ocean siliceous and volcanic rocks (Pumpernickel and Havallah Formations and equivalents) were again obducted or overthrust eastward along the Golconda thrust over equivalent-age rocks on the shelf, which, at that time, included deposits on the eroded remnants of the Antler orogeny (Silberling, 1973; Silberling and Roberts, 1962). Structures associated with the Sonoma orogeny occur mainly in the northwestern part of the Death Valley region (fig. 3), but as research is being vigorously pursued, evidence for this tectonic event may be established along the western marginal area well into San Bernardino County, Calif. (Burchfiel and Davis, 1981).

Tectonic events during the post–Early Triassic in Esmeralda and Nye Counties, Nev., include mainly eastward thrusting and associated folding with generally north-south strike, which was a change from the northeasterly strike of earlier deformations. In Inyo County, Calif., thrusting and folding indicate shortening toward the northeast. Thrusting of probable Late Triassic–Early Jurassic age is recorded in the southern part of the Death Valley region (Clark Mountain Range) (Burchfiel and others, 1970) and in the western part (Inyo and northern Panamint Mountains and Slate Range) (Dunne and others, 1978). Jurassic compression is recorded in northwestern Nye County, Nev., and eastern Inyo County, Calif., by isoclinal folding, imbricate thrusting, and the synorogenic Dunlap Formation (Ferguson and Muller, 1949; Speed, 1978a, b). Thrust faults in Clark County, Nev., and Inyo, and San Bernardino Counties, Calif., also have moved during Late Jurassic to Late Cretaceous (Burchfiel and Davis, 1971, 1975, 1981; Burchfiel and others, 1974, 1983; Dunne and others, 1978; Fleck, 1970). The thrust-faulted terrane in the southeastern one-half of the Death Valley region (fig. 3) involves several regional east-directed, near-bedding thrusts that flatten at depth westward, and that bring upper Precambrian and lower Paleozoic strata over upper Paleozoic and lower Mesozoic strata. This terrane is a part of the Sevier orogenic belt and its hinterland (Armstrong, 1968), and it probably was tectonically active rather continuously from Middle Jurassic to the end of the Cretaceous. Comparable terranes along the western edge of the Death Valley region involve southwest-dipping thrust faults



EXPLANATION

E — EAST LIMIT OF MIOGEOSYNCLINAL SHELF; WEST LIMIT OF CRATONAL PLATFORM--Late Precambrian to Late Cretaceous

W — WEST LIMIT OF MIOGEOSYNCLINAL SHELF; WEST LIMIT OF GRANITIC ROCKS OF CONTINENTAL CRATON--Early and Middle Proterozoic

ROBERTS MOUNTAIN THRUST FAULT (LEADING EDGE) OF ANTLER OROGENY--Late Devonian to Early Mississippian. Sawteeth on upper plate

GOLCONDA THRUST FAULT (LEADING EDGE) OF SONOMA OROGENY--Late Permian to Early Triassic. Sawteeth on upper plate

MAJOR THRUST FAULTS OF SEVIER OROGENY, CRETACEOUS, AND OLDER UNNAMED THRUSTING EVENTS

1 Butte Valley
2 Dry Lake
3 Gass Peak
4 Keystone
5 Last Chance
6 Lee Canyon
7 Luning
8 Leyton Well
9 Mine Mountain and CP
10 Muddy Mountain-Glendale
11 Pahranagat Range
12 Paradise
13 Racetrack
14 Silver Peak
15 Spotted Range

MAJOR STRIKE-SLIP FAULTS--Cenozoic. Arrows indicate direction of relative movement

SHEAR ZONE--TM, Towne Pass-Manly Pass

NORTHEAST MARGIN OF WALKER LANE WHERE RELATIVELY WELL DEFINED

DVA DEATH VALLEY AULACOGEN AREA--Late Precambrian

FIGURE 3.—Tectonic features of the Death Valley region and vicinity, Nevada and California.

that bring rocks of Precambrian and Paleozoic age over rocks of Paleozoic and Mesozoic age. Plutonic rocks that are both displaced by thrusting and intruded into the thrust zones indicate at least two episodes of such faulting, the first apparently in Middle Triassic time and the last in Cretaceous time (Dunne and others, 1978).

In contrast to the Mesozoic, which was a time of compressional tectonism, the early Cenozoic was a time of regional uplift and erosion, and the middle to late Cenozoic was a time of extensional tectonism and volcanism. Numerous papers have appeared in the last several years that deal with the origin and evolution of the crust during late Cenozoic extensional tectonism from the geological as well as geophysical viewpoints (Eaton, 1982; Stewart, 1978; Thompson and Burke, 1974; Zoback and others, 1981). In the Death Valley region, apparently the earliest record of deformation consists of the Eocene or Oligocene coarse conglomerates (Cornwall and Kleinhampl, 1964; Hunt and Mabey, 1966) at the base of the Tertiary section; these conglomerates usually are overlain by volcanic sequences. Most middle Cenozoic deformation involved normal faulting and stratal tilting and was related to volcano-tectonic and caldera depressions (Stewart, 1980, p. 112) associated with regional extension and voluminous ash-flow eruptions (Lipman and others, 1972; Zoback and others, 1981). The period of normal faulting that produced the modern Basin and Range topography present everywhere within the Death Valley region began about 17 m.y. ago (Christiansen and Lipman, 1972; Ekren and others, 1968; McKee, 1971; Stewart, 1978) and has continued to the present. Strike-slip faults of late Cenozoic age also are prominent (fig. 3); for example, in eastern Mineral County, Nev., associated with the Walker Lane structural zone (Hardyman and others, 1975); in Clark County, Nev.,the Las Vegas shear zone (Longwell, 1960); in Inyo County, Calif.,the Furnace Creek–Death Valley fault system (Stewart, 1967); and in San Bernardino County, Calif., the Garlock fault (Davis and Burchfiel, 1973). A view of the Garlock fault scarp along the southern side of the Slate Range is shown in figure 4. Major normal faults, those of large displacements and major topographic effects, trend northward in the northeastern one-third of the Death Valley, lack regional trend in the central one-third, and trend northwestward in most of the southwestern one-third of the region, with the exception of the north-oriented Towne Pass–Manly Pass shear zone that appears to underlie much of Panamint Valley in Inyo County, Calif. (fig. 3). The effect of mainly right-lateral movement appears to increase in a westerly direction across the region. Late Pleistocene, Holocene, and historic faulting indicate the persistence and widespread occurrence of tectonic deformation that has characterized this part of the Basin and Range province since the Miocene (fig. 5).

Late Cenozoic tilting and warping also is evident in some of the western parts of the Death Valley region. Tilting of strata over a time span of 2.2 yr in mountains east and west of Death Valley was found to be measurable though erratic; calculations of the long-term tilt-rates based on such short-term data were unreasonable, though the directions approximate those indicated by the nearby strata (Greene, 1966). Resurveys along bench-mark lines in the Slate Range-Panamint Valley area also found short-term (0.1–1.0 yr) variations in the rate of altitude changes that ranged from near 0 to 18.3 (mm/km)/yr. Lineal-temporal variations averaged for 3–4 decades were between 0.1 and 0.2 (mm/km)/yr; this rate would theoretically tilt a 1-km-long block of crust to an angle of 45° in 5–10 m.y. (Smith and Church, 1980). Warping for an estimated 40,000 or more years of once-horizontal shorelines, eroded on the western slope of the Panamint Range, produced a 110-m difference in the present altitude of the highest and lowest, which are about 20 km apart (Smith, 1975); this indicates a maximum rate of tilting of 0.14 (mm/km)/yr.

GEOMORPHOLOGY

The Death Valley region includes terrain as high as 3,600 m above sea level and as low as 86 m below it. Most of the mountains and valleys have distinct northwest trends, which reflect the late Cenozoic structural grain, though the trends of intermediate-scale topographic features are quite variable. The overall relief, however, documents this area as one of marked late Cenozoic tectonic activity with faults accountable for much of the topographic relief although a generally unmeasurable crustal warping also probably was involved.

Only the hydrologic subunit that includes Las Vegas (ground-water unit DV–01) drains externally. The remaining subunits drain into local depositional centers, usually marked by playa lakes. If these topographically closed basins contain buried saline deposits, this probably confirms that they are hydrologically closed as well. None of the closed basins in the southeastern one-half of ground-water unit DV–03, however, appear to have had significant lakes during pluvial periods (Mifflin and Wheat, 1979), and a lack of saline deposits might only be the result of an inadequate source of water to introduce them. In many basins, however, subsurface drainage introduces salts which later crystallize when capillary processes transport water to the surface where it evaporates, eventually increasing concentration to the point of crystallization. A presence of subsurface salts thus confirms hydrologic closure, whereas their absence may or may not be significant. With the exception of Eureka Valley, all the basins along

FIGURE 4.—Photograph of the Garlock fault scarp on the southern side of the Slate Range. View toward northeast, Brown Mountain on skyline. Fault in this area displaces all but very young alluvium. Sense of fault is left lateral, and stream channels in this area have been offset laterally 5–25 m (Clark, 1973). Photograph by John S. Shelton (1961).

the western edge of ground-water unit DV–03 contain subsurface salts.

As noted in Chapter E (Sonoran region, California) of Professional Paper 1370, landforms and even "fragile" geomorphic surfaces persist for long periods in the desert environment. Evidence developed in areas just west of the Death Valley region, however, indicates that some parts of the present desert have received runoff from high mountains (2,500–4,400 m) that was as much as 10 times the present runoff (Smith and Street-Perrott, 1983). Landforms in areas lying in the future path of such increased runoff would certainly be altered or destroyed more rapidly than under present climatic conditions. Evidence from desert packrat middens, however, indicates that during the last 40,000 yr, while the lower desert mountains and valleys were effectively more moist than at present and were generally characterized by a winter-precipitation regime, they may not have received greatly increased rain or snow.

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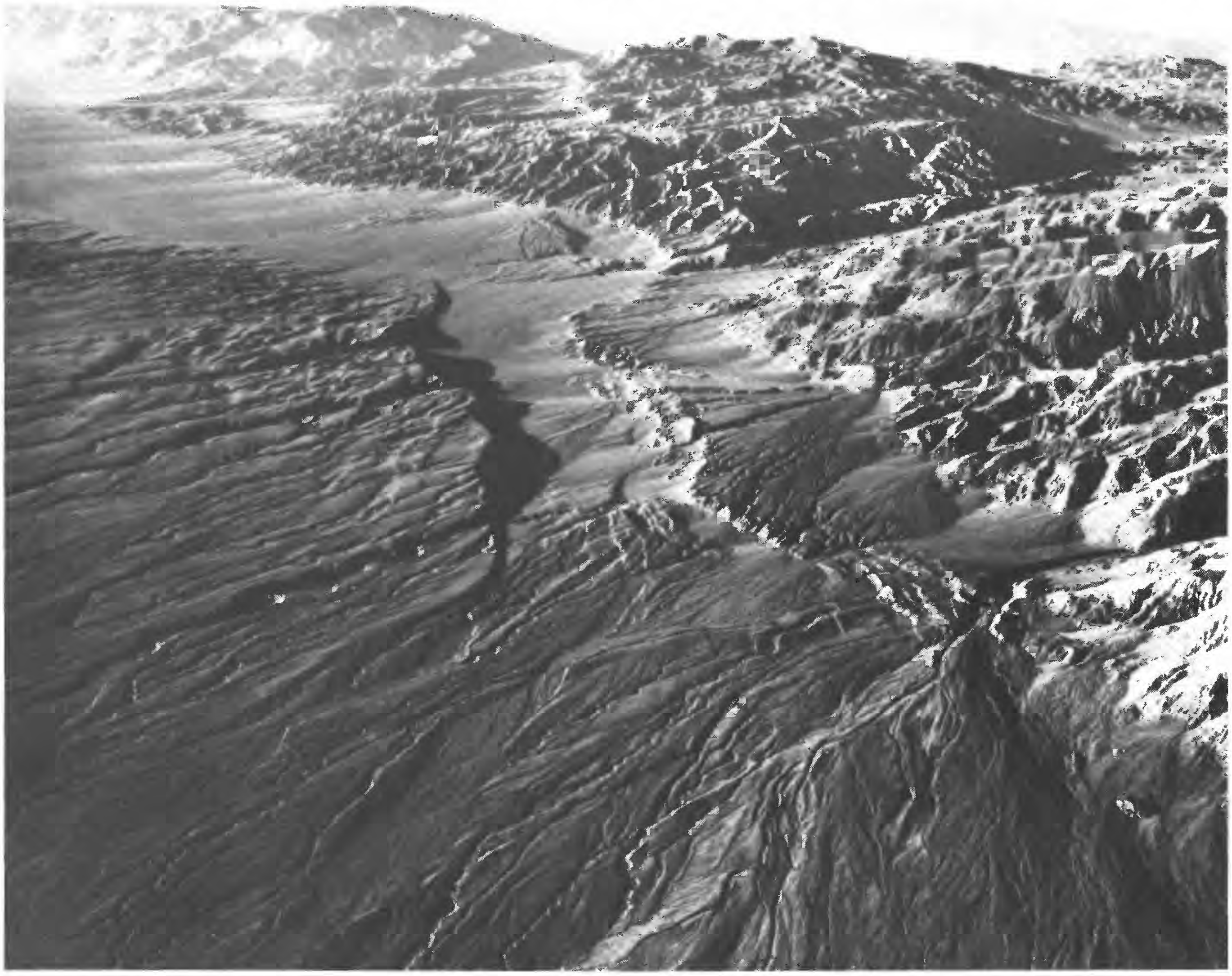

FIGURE 5.—Photograph of Wildrose graben looking north along the eastern side of Panamint Valley. Graben is about 1 km wide, 7 km long, and 70 m deep. Walls of graben expose Pleistocene gravels derived from Panamint Range to the east. Photograph by John S. Shelton (1961).

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POTENTIAL HOST MEDIA FOR RADIOACTIVE WASTE

By K.A. Sargent

Host media considered to have potential in the Death Valley region, Nevada and California, include granite and other coarse-grained plutonic rocks, ash-flow tuff, and basaltic and andesitic lava flows. A few shallow, fine-grained silicic intrusions occur in the region and may have potential as host rocks. Argillaceous sedimentary and metasedimentary rocks generally are steeply dipping, folded, or complexly faulted and would need to be carefully evaluated for potential as host rock. Salt and other evaporitic deposits of sufficient thickness and depth to be host rocks are not known to occur in the region. Most prospective host rocks mentioned above and basin fill have potential as host media in the unsaturated zone. Outcrop areas of potential host rock and areas believed to have thick unsaturated zones in the Death Valley region, Nevada and California, are shown on plate 3.

INTRUSIVE ROCKS

Granitic rocks of Tertiary, Mesozoic, and Precambrian age occur widely throughout the region (pl. 3). For a summary of granitic rocks in the Death Valley region see Hills (1984), Sargent and Roggensack (1984a), and the "Geology" section of this chapter.

The Precambrian crystalline rocks of the Death Valley region are largely granitic gneisses and schists, which have been extensively sheared and mylonitized. For the most part, Precambrian rocks have little or no potential for repository siting in this region.

In ground-water unit DV-01, Mesozoic and a few Tertiary intrusive rocks occur as massive plutons; some of the larger bodies will be discussed here. The Boulder City pluton is a 13-m.y.-old granodiorite that intrudes Tertiary volcanic rocks. The pluton is extensively faulted and brecciated. Other large Tertiary plutons in ground-water unit DV-01 occur in the Eldorado and Newberry Mountains where they intrude Precambrian granitic gneiss and schist and locally are transected by rhyolite and diabase dikes. Part of the complex Teutonia batholith is present in the southwesternmost part of ground-water unit DV-01 and extends into ground-water unit DV-03. It is composed of a considerable variety of coarse-grained igneous rock types such as hornblende gabbro, quartz monzodiorite, granodiorite, monzogranite, and syenogranite. The complex is of middle to late Mesozoic age and possibly postdates much of the major thrusting and mylonitization in the area.

The Kingston Range biotite monzogranite is a relatively large Tertiary intrusive body located in the western part of ground-water unit DV-02 and in the southeastern part of ground-water unit DV-03. Its large area of unsaturated rocks and young age make this granite a good prospect for further investigation.

Ground-water unit DV-03, the largest unit, has the smallest density of exposed granitic masses. Widely scattered and sparse in the northern part of the unit, the intrusions are Precambrian, Mesozoic, and Tertiary in age. In the northern part of ground-water unit DV-03, the Cactus Range pluton of granodioritic and melanodioritic composition and Tertiary age is extensively propylitized and altered. The Climax and Gold Meadows stocks are hydrothermally altered Cretaceous quartz monzonite located in the Nevada Test Site. The Climax stock is the site of a U.S. Department of Energy test for the storage of spent nuclear fuel. The tests are being conducted at about 420 m below the surface, a depth that is above the water table. Elsewhere in southern Nye County are two relatively small exposures of coarse-grained intrusive rocks associated with calderas.

In Esmeralda County, Nev., in the western part of ground-water unit DV-03, the Sylvania pluton, which is composed of Jurassic coarse-grained adamellite, intrudes Precambrian sedimentary rocks. Numerous small exposures of Tertiary and Mesozoic granitic and fine-grained siliceous intrusive rocks occur in the region, but are not well described in the literature. Granite in the California part of the unit is mostly of Mesozoic age and is described as locally fractured or sheared; however, some quartz monzonite is massive and unfoliated, such as in the Soda Mountains (southernmost part of ground-water unit DV-03) and at Manly Peak, southern Panamint Range, along the border with ground-water unit DV-04. A large pluton southeast of Silurian Lake is a massive, unfoliated quartz monzonite believed to have been emplaced after thrust faulting. A quartz monzonite near Sugarloaf Peak southwest of Death Valley is reported as a massive body. Tertiary biotite monzogranite and granite east and west of Death Valley in the Black Mountains and in the Panamint Range, respectively, may be structurally sound. These Tertiary bodies intrude foliated and faulted Precambrian metasedimentary and metaigneous rocks. Large Jurassic or Cretaceous granitic plutons, or both, occur in the Granite and Owlshead Mountains and Avawatz Range in the southern part of ground-water unit DV-03.

The Triassic intrusive rock of the Cottonwood Mountains, in the western part of ground-water unit DV-03, northern part of ground-water unit DV-04, and southeastern part of ground-water unit DV-05, is the Hunter Mountain pluton composed of quartz monzonite. The pluton has more than 1,200 m of relief. Numerous smaller plutons, laccoliths, and plugs are present in ground-water unit DV-03. Many could be large enough at depth to be suitable for repository siting.

In ground-water unit DV-04, granitic rocks are common in all the bounding ranges. In the Slate, Argus, and Coso Ranges, on the western side of the unit, Mesozoic quartz monzonite is widespread and locally intruded by swarms of dikes. In the Slate Range the pluton is composed of flat-lying granitic sheets a few to hundreds of meters thick. As described in the discussion of ground-water unit DV-03, the Jurassic pluton at Manly Peak is unsheared and unbrecciated; however, topographically lower and exposed just above the floor of Panamint Valley, the Triassic granodiorite is sheared and brecciated.

In ground-water unit DV-05 around Saline Valley, there are several large plutons. One large body west of the valley is the Paiute Monument pluton, a hornblende-biotite monzogranite of Jurassic age. It intrudes Jurassic Hunter Mountain Quartz Monzonite (mentioned in the discussion of ground-water unit DV-03). A pluton that occurs on the divide with Death Valley and Panamint Valley in the southeastern part of the unit is the western end of the Hunter Mountain pluton mentioned in the discussion of ground-water unit DV-03.

On the divide between ground-water units DV-05 and DV-06 is the foliated and locally faulted King Papoose Flat pluton of Cretaceous age. In the central part of ground-water unit DV-06 is a Jurassic pluton composed of monzonite and diorite. In ground-water units DV-06 and DV-08, a large monzonite to quartz monzonite stock of Jurassic age occurs. This mass, which forms much of the White Mountains, is composed of multiple Mesozoic intrusions and appears to have few structural complications.

In ground-water unit DV-07, the largest plutons exposed include the Jurassic Palmetto pluton (southwestern part of ground-water unit DV-07) and the Cretaceous Belmont and Manhattan plutons (northwestern part of ground-water unit DV-07). These plutons are extensive, locally porphyritic, and unfoliated. Smaller plutons of Triassic to Tertiary age range in composition from granite to diorite. Most are unfoliated although they are locally transected by rhyolite and diabase dikes.

Granitic rocks in ground-water unit DV-08 consist largely of Jurassic and Cretaceous monzonite, quartz monzonite, and adamellite plutons. Very little data exists on their structural condition. The large plutons are the Palmetto (southeastern part of ground-water unit DV-08) and unnamed bodies near the California-Nevada State line.

Mostly small granite exposures occur in ground-water unit DV-09; exceptions are the Lone Mountain Granite and quartz monzonite west of Tonopah, Nev. The large Lone Mountain pluton is of Cretaceous age (63-71 m.y.) and is transected by diabase dikes. Less than 10 km to the southwest of the Lone Mountain pluton is the Weepah pluton, a Mesozoic quartz monzonite.

TUFFACEOUS ROCKS

In California, welded to nonwelded tuffs of limited extent and minimal thickness occur in ground-water units DV-04 and DV-05 and the eastern part of ground-water unit DV-06. Mixed volcanic rocks of Miocene age, possibly containing tuffs as thick as 400 m, occur in ground-water unit DV-03 in the Grapevine Mountains along the Nevada-California State line. In the southern part of ground-water unit DV-01, thin ash-flow tuffs of possibly andesitic composition occur in the Sacramento Mountains and vicinity. Tuffs in California were summarized by Jenness and Lopez (1984).

In Nevada, tuffs are very widespread in large outcrop areas north of lat 37° N. (Sargent and Roggensack, 1984). A few outcrops of welded tuff occur in ground-water unit DV-01. North of Nelson, Miocene rhyolitic ash-flow tuffs are as thick as 250 m. In Eldorado Valley and in the Highland Range, the same tuffs (Tuff of Bridge Spring) are 120 m thick and occur where the depth to water is greater than 150 m.

In the northern part of ground-water unit DV-03 there are abundant tuffs having aggregate thicknesses commonly greater than 1,200 m. Within the Silent Canyon caldera, at Pahute Mesa, drill holes have penetrated more than 4,100 m of volcanic rock, much of it tuff, but including silicic lava flows. Here the unsaturated zone is as much as 700 m thick. The tuffs at Pahute Mesa include Miocene densely welded to nonwelded ash-flow tuff, air-fall tuff, and reworked tuff. Tuff sections generally are thickest within calderas and in topographic lows adjacent to caldera source areas.

Great thicknesses of massive ash-flow tuff occur in the northern and northeastern parts of ground-water unit DV-07 in the Cathedral Ridge (2,400 m) and Kawich calderas (1,000 m). The Bald Mountain caldera in the northeastern part of ground-water unit DV-03 and the Timber Mountain–Oasis Valley caldera complex in the central part of ground-water unit DV-03 also contain thick ash-flow tuffs. Thick unsaturated sections are present in these caldera areas.

In ground-water unit DV-08, the Silver Peak caldera in the Silver Peak Range, contains tuffs as thick as 600 m and a thick unsaturated section. Tuffs adjacent to the caldera may be as thick as 450 m.

In ground-water units DV-07 and DV-09, tuffs are widespread although their caldera sources are not well known. The Toiyabe Quartz Latite of Miocene age, is widespread and commonly greater than 300 m thick in the northern part of ground-water unit DV-09. The tuffs of Rye Patch, probably of Oligocene age, may be as thick as 1,800 m in the southern Monitor Range (ground-water unit DV-07), site of a possible caldera; much of the upper part of the tuff section and the overlying surficial deposits are unsaturated.

BASALTIC ROCKS

Tertiary basalts are widely distributed throughout the Death Valley region (Roggensack and Sargent, 1984; Roggensack and Lopez, 1984). Virtually all the flows are middle Miocene or younger. A few areas are the sites of large outpourings of mafic lava. Generally the aggregate thickness of these large exposures of basaltic flows is about 300 m, but in places it may be as much as 900 m. The thick occurrences are briefly discussed here. The great majority of the smaller, individual basaltic and andesitic flows, however, are less than 60 m in aggregate thickness and have little or no potential for repository siting.

The eastern part of ground-water unit DV-01 contains unusually thick (700–900 m) andesitic lavas and volcanic breccia of Miocene age in the Black Mountains northwest of Lake Mead. Thick basaltic flows also are present in the Mount Davis Volcanics in the McCullough Range and Eldorado Mountains of ground-water unit DV-01. These volcanic rocks are 11–14 m.y. old (Miocene) and have aggregate thicknesses of about 600 m.

Scattered, mostly small, thin basaltic and andesitic flows occur in ground-water unit DV-03. Of these, the most extensive and thickest flows appear to be Pliocene trachyandesite and trachybasalt on the southeastern flank of Timber Mountain in Nevada, where the aggregate thickness is about 300 m, and at a basalt dome west of Timber Mountain where flows may be as much as 250 m thick. In the Greenwater Range, Calif., andesite and basalt flows may be as much as 150 m thick, but the rocks are extensively altered and fragmented.

In the northern part of ground-water unit DV-04 and in adjacent ground-water unit DV-03, both east and west of the northern end of Panamint Valley, Pliocene and Miocene olivine basalt is widely distributed. The total thickness is more than 150 m and the Tertiary flows locally are overlain by Quaternary basalt. In the Saline Range, in the northern part of ground-water unit DV-05 and in the southern part of ground-water unit DV-06, extensive flows of Miocene to Pliocene olivine basalt, andesite, and trachyandesite occur that may be as much as 300 m thick.

Extensive Miocene trachyandesite flows occur in the San Antonio Mountains in the northwestern part of ground-water unit DV-07 and in the eastern part of ground-water unit DV-09. Here flows have an aggregate thickness of about 300 m and are partly in a thick unsaturated section. In the Goldfield Hills, central part of ground-water unit DV-07, more than 240 m of basalt may be present under the Thirsty Canyon Tuff.

In the northern part of ground-water unit DV-09, at Sherman Peak, a trachyandesite and ash-flow tuff sequence is reported to have a combined thickness of about 550 m.

ARGILLACEOUS ROCKS

In Nevada, outcrops of argillaceous rocks of Paleozoic age are scattered throughout ground-water unit DV-03 and in the northern border area between ground-water units DV-07 and DV-09. The argillaceous rocks are tectonically deformed, faulted, and sheared. Because of their structural complexity, their continuity is difficult to define.

Precambrian metamorphosed argillaceous rocks occur in ground-water units DV-02, DV-03, and DV-04. Small scattered outcrops of Cambrian and Mississippian argillaceous rocks occur in ground-water units DV-03, DV-05, and DV-06. Argillaceous rocks were summarized for the California part of the Death Valley region by Johnson (1984), and for the Nevada part by Simpson and others (1979).

UNSATURATED ZONE

The Death Valley region contains the greatest total area and largest contiguous area of unsaturated rocks in the entire Basin and Range province. Depth to water, as confirmed by drill-hole data in southern Nye County, Nev., is as great as 700 m, and numerous holes drilled in basin fill and tuff penetrated more than 450 m of unsaturated section. The great majority of unsaturated rock is in the eastern part of ground-water unit DV-03 and in the central part of ground-water unit DV-01, but relatively large areas of unsaturated rock are present in all of the ground-water units of the region (pl. 3). The primary host media in the unsaturated zones are tuff, granite, basalt, and basin fill.

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QUATERNARY TECTONISM

By K.A. SARGENT and T.L.T. GROSE[2]

Evidence of Quaternary tectonic conditions of the Death Valley region includes data on seismicity, heat flow, Quaternary faulting, and late Cenozoic volcanic activity and vertical movement. Each of these features is depicted in figure 6.

SEISMICITY

A compilation of epicenters for the Death Valley region, by Algermission and others (1983), shows several hundred recorded earthquakes. Of these, 37 have Richter magnitudes (surface waves) of 5 or greater; all but 17 of these occur in the Nevada Test Site where underground nuclear tests at Yucca Flat and Pahute Mesa are known to have produced manmade earthquakes (fig. 6). Several of the earthquakes at the Nevada Test Site with magnitudes of more than 4 are natural.

Of the 17 naturally occurring earthquakes of magnitude 5 or greater, most have their epicenters along the western side of the region. Only one of these large-earthquake epicenters (magnitude 5 or greater) appears to coincide with the surface expression of the Death Valley–Furnace Creek fault. None appear to coincide with the Garlock fault or the Las Vegas shear zone. Even the smaller earthquakes, those with magnitudes less than 5 (Algermissen and others, 1983), appear to have no particular correspondence with these three large faults. Two earthquakes occurred in the Lake Mead area and may be related to a hydraulic connection between impounded lake water and a deep-aquifer system along buried faults (Anderson and Laney, 1975). Outside the Nevada Test Site, the two largest earthquakes, magnitudes 6–7, were east of Owens Valley and southwest of Columbus Salt Marsh in Esmeralda County, Nev., and together with swarms of smaller earthquakes form two large areas with significant strain release in the western and northwestern parts of the region.

The Death Valley region occurs within a broad, rather vaguely defined region of relatively moderate earthquake frequency and areal density, moderate cumulative seismic-strain energy release, and oblique slip between a strike-slip-dominated region to the west and a dip-slip-dominated region to the east (Eaton, 1980; Smith, 1978). Fault-plane solutions indicate significant right-lateral-slip movement in the western part of the Death Valley region and more oblique- or dip-slip movements in the eastern part (Slemmons and others, 1979; Smith and Lindh, 1978), which correspond with geologic observations on faults in the region. Both fault-plane solutions on seismic events and fault geometries indicate a general west-northwest direction of seismotectonic extension in the Death Valley region. This agrees well with other lines of independent evidence of state of stress in the region (Zoback and Zoback, 1980). Throughout the region, focal depths of the earthquakes are usually less than 15 km, being slightly deeper in the western part of the region where strike-slip movement dominates (Eaton, 1980).

Various seismogenic regionalization studies in the Death Valley region indicated that the most notable concentration of earthquake epicenters (Askew and Algermissen, 1983; Ryall, 1977), the most rapid extensional strain rate (Greensfelder and others, 1980), and the greatest number of late Quaternary and historic faults (Nakata and others, 1982) occur in the northwestern part of the Death Valley region. This area is in the southeastern part of the Nevada seismic zone (Gumper and Scholz, 1971; Ryall and others, 1966; Wallace, 1978), the most active seismic zone in Nevada. Seismic activity decreases in a southeasterly direction through the Death Valley region.

HEAT FLOW

Heat-flow measurements for 39 sites were reported for the Death Valley region (J.H. Sass, U.S. Geological Survey, written commun., 1982). Only two of the measurements exceed 2.5 HFU (heat-flow units) (fig. 6). Both are in Inyo County, Calif., one northwest of Death Valley (3.0 HFU) and the other northeast of Owens Lake (18.70 HFU). The larger value probably is associated with a local fault-controlled geothermal convection system. The heat-flow map of Sass (shown in Sargent and Bedinger, 1985, fig. 16) shows the northeastern part of the Death Valley region to have values less than 1.5 HFU and the remainder of the region to have values between 1.5 and 2.5 HFU. The unusually small values in the northeastern part of the region are part of the Eureka heat-flow low of southeast-central Nevada and are believed to be caused by convective loss of heat from an area of unusually well developed ground-water circulation through carbonate aquifers (Lachenbruch and Sass, 1977; Sass and Lachenbruch, 1982).

The regional heat-flow map also shows two small areas in the far northwestern part of the Death Valley

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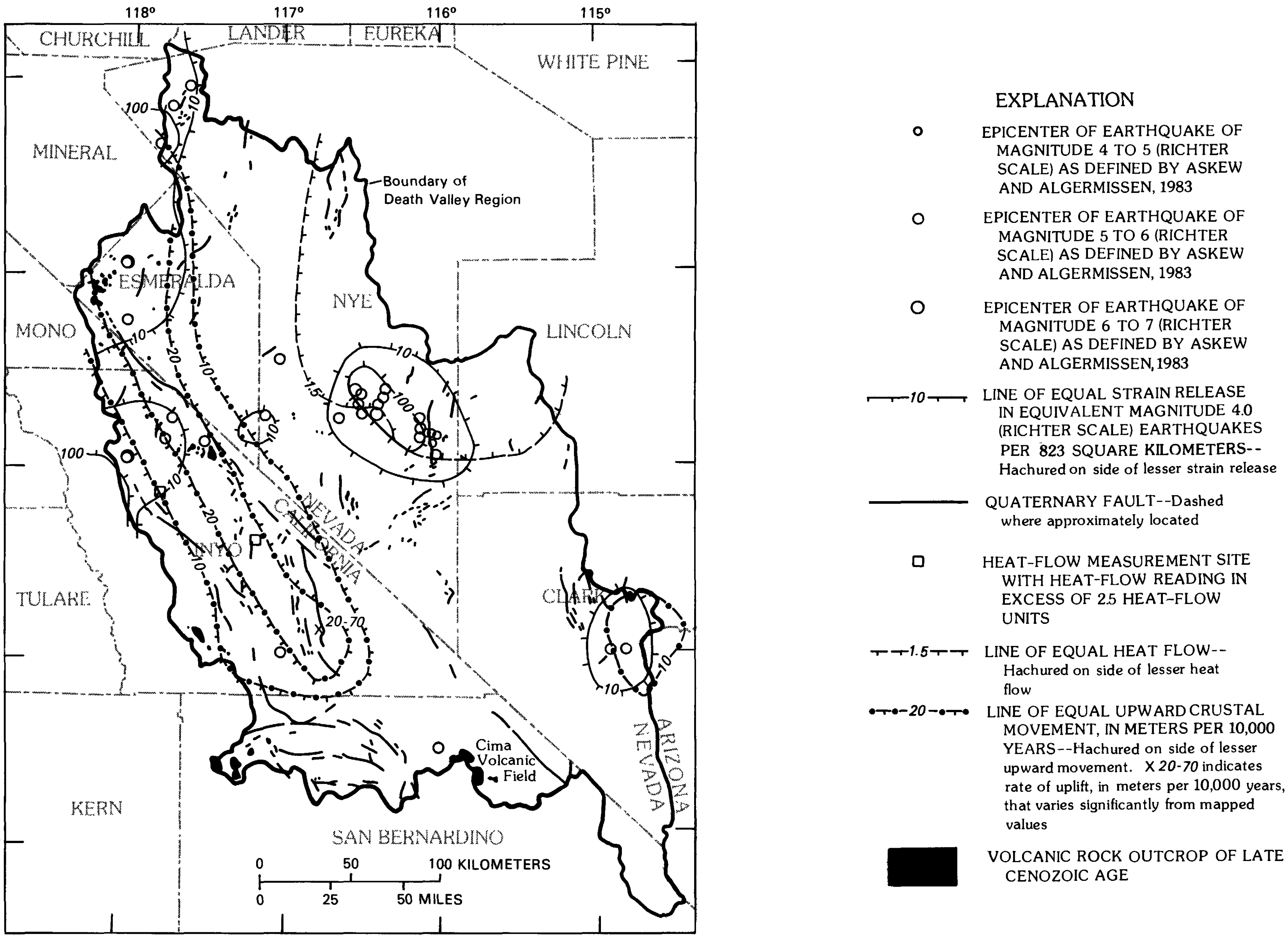

FIGURE 6.—Quaternary tectonic features in the Death Valley region and vicinity, Nevada and California.

region that are interpreted to have greater than 2.5 HFU. Those areas are marginal to the large region of substantial heat flow called the Battle Mountain heat-flow high (Sass and others, 1971).

Within the Death Valley region, conductive heat flow locally is modified by thermal springs. Relative to most adjacent areas, thermal springs are few in number and cool (Berry and others, 1980; Garside and Schilling, 1979; Waring, 1965). Only one, at Tecopa in southeastern Inyo County, Calif., indicates a hydrothermal convection system with temperature greater than 90 °C (Muffler, 1979).

QUATERNARY FAULTING

In regional compilations, Nakata and others (1982) and Jennings (1975) show Quaternary faults unevenly distributed in the Death Valley region (fig. 6). The greatest concentration and longest traces of these faults coincide with, or lie within, the mapped zones of pre-Quaternary faults; examples are the Panamint Valley fault, Garlock fault, and the Death Valley–Furnace Creek fault zone. In addition, the sense of Quaternary displacement on all three faults is the same as the older sense of displacement, apparently indicating continuing or renewed stress fields similar to those in the geologic past. There is no clear correspondence between the location of earthquakes of magnitude less than 4 and Quaternary faults; only in the northwestern part of the region is there a correspondence between the location of the larger earthquakes and Quaternary faults. Faults with historical movement are found in or near Groom Lake, Yucca Flat, and Frenchman Flat, all in or close to the Nevada Test Site. Fault segments showing displacements, no older than 10,000 yr, occur along the Panamint Valley fault, the Garlock fault, the Yucca fault, and two unnamed faults southeast of Beatty, Nev.

LATE CENOZOIC VOLCANICS

Much of the late Cenozoic volcanic activity is along the southern and western edges of the Death Valley region (fig. 6). Most of the volcanic rocks are basaltic flows and cinder cones with minor andesitic, dacitic and rare rhyolitic flows. In the Crater Flat area southwest of the Nevada Test Site the two major cones have ages of about 1.1 and 1.2 m.y., and a third, smaller cone was formed about 0.25 m.y. ago; recent dating shows the smaller cone may be composite and may have continued activity as recent as 25,000 years ago. A small basaltic outcrop west of the Timber Mountain–Oasis Valley caldera complex has a date of 0.45 m.y. The northern end of the Cima volcanic field occurs near the southern edge of the region. The field consists of flows of hawaiite, alkali-olivine basalt, and basanite of late Miocene to Holocene age (Dohrenwend and others, 1984; Katz and Boettcher, 1980). In other areas, volcanic rocks are assigned ages less than 5 m.y. old by stratigraphic position and geologic association with dated rocks (Luedke and Smith, 1981). There appears to be little coincidence of late Cenozoic volcanic activity with Quaternary faulting or recorded substantial seismicity.

VERTICAL CRUSTAL MOVEMENT

Gable and Hatton (1983) depict a northwest-trending area that encompasses Death Valley with vertical upward movement of an adjacent range to the west at a rate of 20 m per 10,000 yr (2.0 mm/yr). One point within Death Valley is shown to be rising at a rate of 20–70 m per 10,000 yr (2.0–7.0 mm/yr), based on geology, geomorphology, and radiocarbon dates (fig. 6). The greater rate of vertical uplift is in a zone that is parallel to the Sierra Nevada and may be related to the erosion and isostatic adjustment of this great uplifted mountain mass.

Gable and Hatton (1983) show a zone of historic subsidence of as much as 2 m in the vicinity of Lake Mead based on leveling data from 1935 to 1950, although the general area is rising at a rate of 1–4 mm/10,000 yr based on geologic data. The subsidence related to the filling of Lake Mead was summarized by Anderson and Laney (1975).

PHOTOLINEATIONS

Studies of linear features by T.W. Offield (U.S. Geological Survey, written commun., 1983) in the Great Basin using Landsat multispectral scanner images show that numerous photolineations parallel or coincide with Quaternary faults, as well as with known older faults. The longest photolineations are expressions of range-front faults and the Las Vegas shear zone. Linear features seen in Landsat images are alignments of both topographic and tonal features; many are related to tectonism and erosion, such as slope breaks caused by faulting; some are stratigraphically controlled erosional features; and still others are of unknown origin.

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GROUND-WATER HYDROLOGY

By M.S. Bedinger, William H. Langer, and J.E. Reed

Climate of the Death Valley region is arid to semiarid. Precipitation on the valley floors of the Amargosa Desert, Death Valley, and basins at lower altitudes in the southern part of the region is less than 70 mm/yr on the average. The annual average precipitation at Furnace Creek Ranch in Death Valley is 50 mm/yr. Precipitation in the mountain ranges is greater, commonly in the range from 100 to 150 mm/yr. Annual precipitation is as much as 500–750 mm in the Sheep Range and Spring Mountains, the highest ranges in the region. Annual free-water surface evaporation is greater than 2,500 mm/yr in Death Valley.

MAJOR HYDROGEOLOGIC UNITS

Basin fill (including the alluvial material of stream valleys) was deposited largely in structural basins (pl. 4). The fill in many basins is greater than 1,300 m thick and may be as thick as 2,000 m. The basin fill consists mostly of nonindurated to semi-indurated terrestrial sedimentary deposits and volcanic material of late Tertiary to Holocene age. The fill contains volcanic flows and ash falls from episodic volcanic activity during the Tertiary and Quaternary Periods. Fine-grained lake deposits, silt, clay, and evaporitic deposits occur in some of the basins.

Volcanic rocks are grouped hydrologically as three units: (1) Ash-flow tuffs, (2) lava flows, and (3) undifferentiated volcanic rocks, all of Tertiary and Quaternary age. Tuffs, of Tertiary age, are widespread in the northern and central parts of the region, with an aggregate thickness of more than 4,000 m. They include densely welded to nonwelded, bedded, reworked, and air fall tuffs. The following discussion of ash-flow tuffs is from Winograd (1971). Welded ash-flow tuffs characteristically have an interstitial porosity of about 5 percent or less. The permeability of welded ash-flow tuff, which commonly is moderate to large, is largely a function of jointing, bedding-plane openings, and partings within the flows. Welded ash-flow tuffs may be important units in the ground-water flow systems of the regions, especially in ground-water unit DV–03 where they are thick and of great areal extent. In contrast, nonwelded ash-flow tuffs may have a large interstitial porosity and small interstitial permeability and function as confining beds. Fractures and joints are virtually absent.

Lava flows primarily are basalt and other mafic rocks of Tertiary and Quaternary age. Columnar jointing and platy fractures are common in the flows that are vesicular to dense. Permeability and porosity is developed along fractures and bedding planes. Individual flows generally are less than 33 m thick; some are less than 1 m thick. Aggregate thicknesses are as much as 1,000 m.

The central part of the Death Valley region is underlain by one of the thickest known sequences of Paleozoic rocks in the Basin and Range province; over 8,000 m of Paleozoic sedimentary rocks are exposed. Winograd and Thordarson (1975), in the area here referred to as ground-water unit DV–03, distinguished in this sequence, from bottom to top, a lower clastic confining bed, a lower carbonate aquifer, an upper clastic confining bed, and an upper carbonate aquifer. Upper Precambrian and Lower Cambrian quartzite, shale, and siltstone compose the lower clastic confining bed. The lower carbonate aquifer is composed of the carbonate rocks of Middle Cambrian age and ranges in saturated thickness from a hundred to a few thousand meters. Argillite, quartzite, and conglomerate of Late Devonian and Mississippian age, compose the upper clastic confining bed, which ranges from 1,300 to 2,600 m in thickness. Carbonate rock of Pennsylvanian and Permian age forms the upper carbonate aquifer. The lower carbonate aquifer is the more extensive aquifer, occurring in a large part of ground-water unit DV–03 and in the northern part of ground-water unit DV–01. In these areas, the lower carbonate aquifer is absent or unsaturated only in outcrop areas or structural highs. Where the lower carbonate aquifer is absent, the lower clastic confining bed is a barrier to regional ground-water flow (Winograd and Thordarson, 1975, pl. 1). The saturated extent of the upper carbonate aquifer in ground-water unit DV–03 is limited to small areas in south-central Nevada, and this aquifer does not have a large effect on regional ground-water flow. Similarly, the upper clastic confining bed is of limited distribution and of only local significance to regional ground-water flow.

Crystalline rocks are widespread; they crop out in many mountain ranges and underlie the entire region at depth. Crystalline rocks include metamorphic rocks and intrusive igneous rocks of Precambrian, Mesozoic, and Tertiary age.

GROUND-WATER FLOW REGIME

Ground-water recharge occurs by infiltration of precipitation and runoff. Recharge in basins in California and Nevada has been estimated as a function of the quantity of precipitation (Rantz and Eakin, 1971; Rush, 1970). Rantz and Eakin (1971) estimated recharge in areas receiving less than 200 mm of precipitation annually to be less than 3 percent of precipitation; they estimated recharge to be 3 percent for areas receiving 200–300 mm and 7 percent for areas receiving 300–380 mm. However, recharge also is a function of such factors as water loss by evaporation and transpiration, rock type and physical character, slope, and soil cover. Recharge by direct infiltration of precipitation to the valley floors that receive 200 mm or less precipitation per year, is believed to be very small (Winograd and Thordarson, 1975, p. C92), but recharge may occur during infrequent large storms that cause runoff locally or at higher altitudes in mountains that adjoin the valley floors. Winograd and Thordarson (1975, p. C86) suggested relatively substantial recharge in outcrop areas of extensively fractured carbonate rock in the mountain ranges and relatively little recharge in outcrop areas of tuff on which a clayey soil has developed.

Natural discharge is by flow to springs, by evapotranspiration in areas where the water level is near the land surface, and by seepage to the Colorado River. The Death Valley region is largely composed of closed topographic basins that are apparently coincident with closed ground-water flow systems of ground-water units DV–02 and DV–04 through DV–09. Ground water in these closed basins flows to playa areas where it is discharged. A part of the region, ground-water unit DV–01, has surface drainage and ground-water discharge to the Colorado River.

Ground-water flow in ground-water unit DV–03 is not coincident with topographic basins. This unit is underlain by the extensive Paleozoic carbonate-rock aquifers and associated confining beds. Because of the effect of the carbonate aquifers in underdraining the area and the effect of structural and lithologic controls in compartmentalization of flow, ground-water flow in ground-water unit DV–03 is complex. Because ground-water flow commonly is not coincident with topographic basins and because the flow systems in the unit are imperfectly known, the unit is large and not subdivided. The ground-water flow conditions in ground-water unit DV–03 are discussed in the following paragraphs.

Subsurface flow between many topographic basins occurs in ground-water unit DV–03. Basins identified by Winograd and Thordarson (1975) that drain to the carbonate-rock aquifers include those of Yucca and Frenchman Flats. By inference, several other closed basins without surface discharge of ground water also are believed to drain to the carbonate aquifer. These are Indian Springs Valley, northern Three Lakes Valley, Emigrant Valley, and Tikaboo Valley, all in ground-water unit DV–03. The areas where ground water infiltrates from the closed basins to the carbonate aquifer are not known. The basins that drain to the underlying carbonate aquifer are identified on plate 5.

Regional interbasin movement of ground water in ground-water unit DV–03 is affected by the deformed nature of the great thicknesses of Paleozoic carbonate and clastic rocks. Major wrench, thrust, and normal faults and folds have been shown to exert marked control on ground-water movement (Winograd and Thordarson, 1968). Compartmentalization of flow in the region by fault blocks containing thick sequences of clastic rocks, and perhaps also shear zones, were demonstrated by Winograd and Thordarson. Large-scale heterogeneities in carbonate-rock permeability have been inferred by Winograd and Pearson (1976) on the basis of carbon–14 isotope analyses of ground water in the Ash Meadows area.

Discharge of ground water from ground-water unit DV–03 occurs in several large areas. Three large natural-discharge areas occur in Sarcobatus Flat, Amargosa Desert, and Pahrump Valley (pl. 5). The ultimate discharge area for ground-water unit DV–03 is Death Valley, the basin of lowest altitude in the region, 86 m below sea level. Discharge at Death Valley occurs to numerous springs and seeps and by evapotranspiration (Hunt and others, 1966; Miller, 1977). Oblique aerial views of Death Valley are shown in figures 7 and 8.

Thermal springs (arbitrarily designated as those with a water temperature greater than 20 °C) are found in the region; many of these springs discharge from zones with substantial permeability in carbonate rock. Both thermal and nonthermal springs characterize the major discharge areas near the Colorado River and in Death Valley, Ash Meadows, Amargosa Desert, and in many smaller basins. The temperature of most of the thermal springs is less than 50 °C, which indicates convective heat flow of ground water rather than locally anomalously high heat flows. Cold springs having 200 L/min or more discharge occur at Ash Meadows and at other localities. Thermal springs and some cold springs are plotted on plate 5.

Ground-water withdrawal is concentrated at pumping centers such as Las Vegas, Pahrump Valley, and Ash Meadows. Many valleys have little or no pumping. Withdrawal is described in reports by Bedinger, Langer, and Moyle (1984) and Bedinger, Harrill, and Thomas (1984).

GROUND-WATER FLOW ANALYSIS

AREAL GROUND-WATER FLOW

The region was separated into hydrogeologic units at the water table based on information from previous studies and summarized in this report, from the geologic

FIGURE 7.—View from the saltpan of Badwater Basin in Death Valley to the northwest across faulted alluvial fans toward the Panamint Range. Growths of phreatophytes occur in a band from the lower left to the middle right of the photograph at the boundary of the saltpan and the alluvial fans. Shortys Well is in the area of vegetation at the center; Tule Spring is in an area of vegetation near the middle right of the photograph. The water table is near the surface at the edge of the saltpan and deepens with distance up the alluvial fans. The growth of phreatophytes marks the area of accessible depths to ground water and salinities within the tolerance of the plants. The phreatophytes are zoned with the more salt-tolerant species near the saltpan. Escarpment of Hanaupah fault shows two stages of displacement. Obvious fault escarpment across center of photograph marks 15-m displacement of older upper Pleistocene fan gravels (No. 2 gravel of Hunt and Mabey, 1966). Small fault (arrow) displaces younger upper Pleistocene fan gravels (No. 3 gravel of Hunt and Mabey, 1966) by as much as 2 m. Photograph by John S. Shelton (1979).

sections constructed for the region (Bedinger and others, 1989), and from water-level contour maps. Relative ground-water traveltimes at the water table were analyzed using the procedure described in Chapter A (Bedinger and others, 1989). Velocities in the hydrogeologic units (pl. 4) are reported as relative velocities because site-specific data are not available. The values of hydraulic properties of the hydrogeologic units and hydraulic gradients used in estimating relative ground-water velocities are listed in table 1.

The hydraulic gradients for the hydrogeologic units are representative gradients taken from the water-level contour map. The ratio of hydraulic conductivity to effective porosity was estimated using the values in Chapter A (Bedinger and others, 1989) and modified from the lithologic and hydrologic description of the units, and further modified during the verification of the cross-sectional and areal-flow models.

Relative ground-water traveltimes are shown on plate 5. The ground-water divides and flow paths were

FIGURE 8.—View of Death Valley from near the southern end of the valley. Smith Mountain is in right foreground, Mormon Point at center of photograph, and Grapevine Mountains in middle background. Death Valley is the ultimate discharge area for a large part of the Death Valley region. Amargosa River flows from lower left, away from observer toward Badwater Basin (altitude 86 m below sea level), white rock-salt area in center of valley in upper middle part of photograph. Photograph by John S. Shelton (1979).

estimated from the available ground-water level data, which in many parts of the region are very sparse. Lacking water-level data, the ground-water divides and flow paths were estimated from topographic divides and the lithologic units at the water table. Evidence for barriers to ground-water flow has been demonstrated by Winograd and Thordarson (1968, 1975) and Waddell (1982). Other flow barriers, as yet unidentified, undoubtedly exist in the region, especially in ground-water unit DV–03. Flow arrows indicate paths at the water table along which the relative traveltimes to these discharge areas were calculated using methods described in Chapter A (Bedinger and others, 1989). Major discharge areas, large springs, and evapotranspiration areas also are shown on plate 5. Several closed basins have no surface discharge areas. Flow from the water table in these basins is inferred to be downward to carbonate rocks. These basins are indicated diagrammatically on plate 5 with diamond-shaped symbols. The diamond-shaped areas are not intended to indicate the actual location or distribution of areas of downward flow to the regional aquifer, but to simply show that the basin does not have surface discharge and that it is inferred that the basin discharges by underflow.

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 cross section is given

TABLE 1.—*Hydraulic properties of hydrogeologic units and hydraulic gradients used in estimating relative ground-water velocities at the water table*

[K, hydraulic conductivity, in meters per day; ϕ, effective porosity; --, no data]

Hydrogeologic unit	Map symbol (pl. 4)	K/ϕ (meters per day)	Hydraulic gradient
Basin fill	a	6×10^{1}	0.003
Crystalline rocks:			
Granitic rocks	g	2×10^{-1}	.03
Mafic intrusive rocks	z	2×10^{-1}	.03
Metamorphic rocks	m	2×10^{-1}	.03
Mixed rocks:			
Large percentage of carbonate rocks.	I	1×10^{1}	.003
Large percentage of crystalline rocks.	II	2×10^{-1}	.03
Sedimentary rocks:			
Coarse-grained clastic rocks.	s	2×10^{-1}	.03
Fine-grained clastic rocks.	f	2×10^{-6}	--
Carbonate rocks	c	1×10^{1}	.003
Volcanic rocks:			
Undifferentiated	v	1×10^{-1}	.03
Lava flows	b	3×10^{0}	.03
Ash-flow tuff	t	1×10^{-1}	.03

in Chapter A of Professional Paper 1370 (Reed, 1989). The map location of hydrogeologic sections and the modeled sections are shown cn plate 6. The values of hydraulic properties of the rock units in the hydrogeologic sections used in analysis of the ground-water flow are given in table 2.

Distribution of rock units, relative traveltime, and stream functions are given on the hydrogeologic sections. Relative traveltimes are given in intervals of one order of magnitude from 10^1 and longer. Numbers indicate the relative traveltime from points on the line to the discharge area. Stream functions show the directions of ground-water movement and the numbers indicate relative quantity of flow in the section below the flow line.

The hydrogeologic sections provide a more realistic concept of the flow paths and traveltime between widely spaced points in the region than does the map of traveltime at the water table. As seen from the hydrogeologic sections, the flow paths in the divide areas of the flow system dip 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 10^8. 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 10^4 or greater exist at the water table in the hydrogeologic sections.

Evidence exists for large-scale variations in permeability in the carbonate rocks (Winograd and Pearson, 1976) and for barriers to the regional ground-water flow (Winograd and Thordarson, 1968; Waddell, 1982). Zones with substantial permeability that may exist locally in the carbonate rocks may have a great effect on flow distribution and traveltimes in the carbonate rocks. Because the distribution and extent of channeling in the carbonate rocks are not known, the permeability and effective porosity of the carbonate rocks were modeled as constant values, which are believed to represent averages of these hydrologic properties.

QUALITY OF GROUND WATER

The quality of ground water in the Death Valley region is characterized by the areal distribution of dissolved solids (pl. 7) and predominant chemical constituents in solution (fig. 9). These maps are generalized from those by Thompson and others (1984) and Thompson and Chappel (1984) compiled from the water-quality files of the U.S. Geological Survey (WATSTORE) and published reports. The data are mostly from

TABLE 2.—*Hydraulic properties of units modeled in hydrogeologic sections*
[K, hydraulic conductivity, in meters per day; ϕ, effective porosity; --, no data]

Hydrologic unit	Symbol (pl. 6)	Hydrogeologic section					
		A–A'		*B–B'*		*C–C'*	
		K/ϕ	ϕ	K/ϕ	ϕ	K/ϕ	ϕ
Upper coarse-grained basin fill.	a	1×10^{1}	1.8×10^{-1}	1×10^{1}	1.8×10^{-1}	2×10^{1}	1.8×10^{-1}
Lower coarse-grained basin fill.	A	2×10^{-2}	1.8×10^{-1}	1.2×10^{0}	1.8×10^{-1}	1×10^{-1}	1.8×10^{-1}
Ash-flow tuff	t	--	--	4×10^{-4}	3.5×10^{-1}	--	--
Carbonate rocks	c	--	--	--	--	3×10^{-3}	1×10^{-1}
Crystalline rocks, upper part of section.	G	5×10^{-4}	3×10^{-3}	5×10^{-4}	3×10^{-3}	5×10^{-4}	3×10^{-3}
Crystalline rocks, lower part of section.	g	3×10^{-7}	1×10^{-4}	3×10^{-7}	1×10^{-4}	3×10^{-7}	1×10^{-4}
Undifferentiated volcanic rocks.	v	4×10^{-4}	4×10^{-3}	4×10^{-3}	4×10^{-4}	--	--
Lava flows	b	5×10^{-4}	1.5×10^{-3}	5×10^{-1}	1.5×10^{-1}	--	--
Coarse-grained clastic rocks.	s	3×10^{-2}	1.8×10^{-1}	3×10^{-2}	1.8×10^{-1}	--	--
Fine-grained clastic rocks.	f	--	--	--	--	--	--

nongeothermal springs and wells less than 150 m deep completed in alluvial and basin-fill deposits. In areas where data are not available, the water-quality characteristics were estimated from the position in the ground-water flow system and the lithology of the local bedrock.

Dissolved-solids concentration is generally less than 500 mg/L except beneath the surfaces of some playa lakes, where ground water may contain more than 500 mg/L of dissolved solids. Concentrations between 1,000 and 3,000 mg/L also occur in the areas near Lake Mead and the Colorado River. Dissolved-solids concentrations commonly are 1,000–3,000 mg/L in playa areas, and ground water of more than 3,000 mg/L of dissolved solids is found in a few playas such as Death Valley, Columbus Salt Marsh, and Clayton Valley.

The concentration of dissolved solids of most ground water in consolidated rocks of the region probably is less than 500 mg/L. The water-quality data from four deep wells in southern Nevada, as summarized by Winograd and Thordarson (1975), indicated no significant increase in dissolved-solids concentration of water in the lower carbonate aquifer to depths of a few thousand meters.

Sodium bicarbonate and calcium-magnesium bicarbonate type waters occur throughout about 90 percent of the region. Mixed-cation sulfate and mixed-cation chloride type waters occur in and near natural discharge areas and generally correspond to areas of maximum dissolved-solids concentration.

PLEISTOCENE HYDROLOGIC CONDITIONS

The climate of glacial epochs during the Pleistocene in the Basin and Range province has been estimated from evidence from plant debris and relict lake shore lines. Spaulding (1984) has made a study of climates at times during the past 45,000 yr from plant remains in pack-rat middens at the Nevada Test Site and vicinity. Climates have been estimated from hydrologic budgets for the full glacial climate of Lake Spring in Spring Valley, Nev. (Snyder and Langbein, 1962), of Lake Lahontan, Nev. (Antevs, 1952; Benson, 1978), and of many late(?) Pleistocene lakes in Nevada by Mifflin and Wheat (1979). These investigations concluded that the climate during glacial epochs was cooler with greater precipitation than present. Other investigators have concluded that the glacial climate in the Basin and Range province was much cooler than present with no increase, or even a decrease, in precipitation (Galloway, 1970; Brakenridge, 1978).

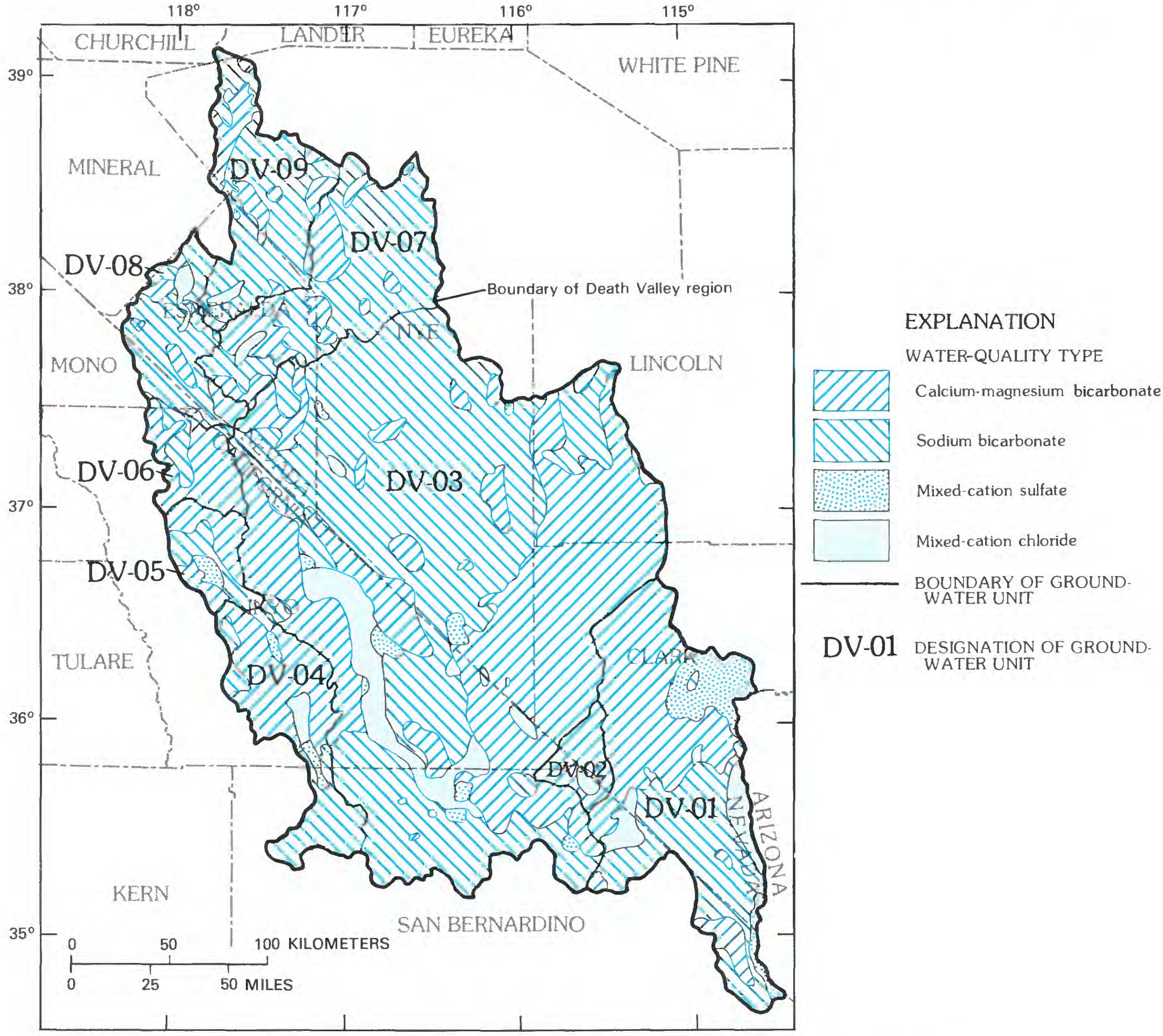

FIGURE 9.—Distribution of chemical types of ground water in the Death Valley region.

Compilation of data on Pleistocene lakes and marshes in the Basin and Range province (Williams and Bedinger, 1984) shows that Pleistocene lakes occupied several closed basins in the Death Valley region. Lake Manly, the largest, occupied the floor of Death Valley, and Panamint Lake occupied Panamint Valley in ground-water unit DV-04. Evidence of smaller Pleistocene lakes has been identified in ground-water units DV-06 (northwestern one-half), DV-07, DV-08, and DV-09. Evidence of three Pleistocene lakes has been found in the northern part of ground-water unit DV-03. With the exception of Groom Lake, no Pleistocene lakes are known to have occupied closed basins that drain from the water table to the underlying carbonate-rock aquifer. Marshes are believed to have occupied parts of valley floors during the Pleistocene in the Amargosa Desert (ground-water unit DV-03), Sarcobatus Flat (ground-water unit DV-03), and the basins in ground-water units DV-05, DV-07, DV-08, and DV-09. Winograd and Doty (1980) have shown that major changes in altitude and location of ground-water discharge actually occurred during the late(?) Pleistocene. These changes are attributed to both climate and tectonism.

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MINERAL AND ENERGY RESOURCES

By B.T. Brady

The Death Valley region contains metallic mineral deposits that are of several ages and occur in diverse geologic environments. These mineralized areas commonly contain precious-metal deposits and base metals in replacement deposits. Contact tungsten deposits are of significance locally. One of the most important world sources of rare-earth elements is being mined currently near Mountain Pass, San Bernardino County, Calif. Large deposits of magnesite and brucite are mined near Gabbs in northwestern Nye County, Nev. Molybdenum is being mined currently at Hall north of Tonopah, Nev. Fluorspar and barite have been produced intermittently from a few principal localities in the study area. Talc mining is important in the Death Valley region. An important domestic and world lithium resource is the brine pumped from sediments beneath Silver Peak Marsh, central Esmeralda County, Nev. Borates, salt, and gypsum have been produced locally from evaporite deposits. Two Known Geothermal Resource Areas (KGRA) and many geothermal occurrences are present in the study area. Small tonnages of coal have been mined in the Coaldale field, Esmeralda County, Nev. No additional occurrences of coal or any productive oil, gas, carbon dioxide, or helium wells are identified at present in the study area.

METALLIC MINERAL RESOURCES

The metallic mineral districts mentioned in this report are those areas depicted by Wong (1983a, b), and their locations are shown on plate 8. The mineral district boundaries enclose areas of productive workings; however, they do not indicate the limit of mineralized rock. A summary of the principal commodities, modes of occurrence, and general references for the mineral districts in the Death Valley region is presented in tables 3 and 4 (modified from Wong, 1983a, b).

At least 113 metal-mining districts are located in the Death Valley region, and more than 25 commodities were produced from mines in the region. Several types of mineralization are important locally in rocks ranging from Precambrian to Quaternary in age.

The value and relative importance of metal production in the Death Valley region varies by district and through time. The principal metallic elements that have been produced include gold, silver, copper, molybdenum, lead, zinc, and tungsten. The most significant metallic mineral production to date in the study area has come from the Goldfield district, Esmeralda County, Nev., and the Tonopah district, principally in Nye County, Nev. Smaller, although still very important, production came from extensively developed mines in the following districts: Goodsprings (Clark County), Tem Piute (Lincoln County), Manhattan and Tybo (Nye County), Silver Peak (Esmeralda County), in Nevada; and Mountain Pass (San Bernardino County), and Darwin and Cerro Gordo (Inyo County), in California. The mineralized areas mentioned above have each yielded concentrates worth at least $10 million, and in some cases, as much as $1 billion (Albers and Stewart, 1972; Cornwall, 1972; Longwell and others, 1965; Mardirosian, 1974a, b; Tschanz and Pampeyan, 1970).

Gold and silver were produced from several mines in the Death Valley region as early as the 1860's, and by the early 1900's many of the original discoveries were substantially depleted. More than 124.4 Mg of gold and at least 43.5 Mg of silver were produced from small lodes in silicified and alunitized north-trending fractures in the Tertiary Milltown Andesite in the Goldfield district in Nevada (Albers and Stewart, 1972). The peak production period in the Goldfield district was from 1905 through 1912, and smaller quantities of ore were mined locally as late as 1955. The cumulative value of metals yielded from mines in the Goldfield district exceeds $89 million, and this amount accounts for more than 75 percent of the total nonfuel mineral production in Esmeralda County to 1972 (Albers and Stewart, 1972).

At least 3,110 Mg of silver (Kleinhampl, 1964) and 35.9 Mg of coproduct gold were mined in the Tonopah district in Nevada (Bergendahl, 1964). These fault-controlled argentiferous replacement deposits near Tonopah occur in altered Tertiary rhyolite and andesite, and they have yielded precious- and base-metal concentrates worth more than $100 million (Albers and Stewart, 1972). Although the Goldfield and Tonopah districts contain deep workings, the most productive ore shoots in these areas occurred within 300 m of the surface. In recent years, the Anaconda openpit mine in the San Antonio district north of Tonopah has produced a substantial quantity of molybdenum and some copper.

In addition to the important production of precious metals at Goldfield and Tonopah, large quantities of gold and silver have come from mineral deposits in the Silver Peak district, Esmeralda County, and the Manhattan district, Nye County, Nev. Precious-metal lodes in the Silver Peak district occur as irregular quartz masses and thin anastomosing veins in locally

TABLE 3.—*Metallic mineral districts of the Death Valley region of Nevada*

[Commodities listed in the commodities column are abbreviated as follows: Ag, silver; As, arsenic; Au, gold; B, boron; Ba, barium; Bi, bismuth; Cd, cadmium; Co, cobalt; Cu, copper; F, fluorine; Fe, iron; Hg, mercury; K, potassium; Mg, magnesium; Mn, manganese; Mo, molybdenum; Pb, lead; Pt, platinum; Re, rhenium; Sb, antimony; Se, selenium; Sn, tin; Sr, strontium; Te, tellurium; Th, thorium; Ti, titanium; U, uranium; V, vanadium; W, Tungsten; Zn, zinc. These data are from Wong (1983b), and they are preliminary and subject to revision]

Mining district	Commodities	Deposit type	Host rock	References
Clark County				
Alunite (Railroad Pass, Vincent).	Au, Ag, Pb, Cu, Mn, Alunite.	Disseminated Vein	Quartz monzonite Andesite	Longwell and others, 1965.
Charleston	Ag, Pb, Zn	Vein Disseminated	Dolomitized limestone Dolomitized limestone	Longwell and others, 1965.
Crescent (Crescent Peak).	Au, Ag, Pb, Cu, Mo, U, Th.	Vein Disseminated	Granite, Gneiss Prospect Mountain Quartzite, quartz monzonite.	Hewett, 1956; Longwell and others, 1965; Ransome, 1907; Schilling, 1962; Vanderburg, 1937a.
Eldorado (Eldorado Canyon, Colorado, Nelson).	Au, Ag, Pb, Zn, Cu.	Vein Disseminated Breccia zone	Gneiss, schist, quartz monzonite, andesite. Quartz monzonite Quartz monzonite	Longwell and others, 1965; Ransome, 1907; Vanderburg, 1937a.
Gass Peak	Au, Ag, Pb, Zn.	Shear zone	Dolomitized limestone	Hewett and others, 1936; Longwell and others, 1965.
Goodsprings (Yellow Pine, Potosi).	Au, Ag, Pb, Zn, Cu, Mo. V, U, Pt, Co, Ti, Hg, Pb.	Vein Disseminated Breccia zone Replacement Contact metamorphic.	Dolomitized limestone, granite porphyry. Limestone, dolomite Dolomite, limestone Dolomite breccia, limestone. Limestone	Albritton and others, 1954; Bailey and Phoenix, 1944; Beal, 1963; Hewett, 1931; Hewett, 1956; Knopf, 1915; Lincoln 1923; Longwell and others, 1965; Schilling, 1962.
Las Vegas	Mn, Au, Ag, Pb, Cu.	Bedded	Sandstone and claystone of the Muddy Creek Formation.	Longwell and others, 1965; Trengove, 1959; Vanderburg, 1937a.
Searchlight	Au, Ag, Pb, Zn, Cu, Mo.	Vein	Andesite porphyry, gneiss, hornfels.	Callaghan, 1939; Longwell and others, 1965; Schilling, 1962.
Sunset (Lyons)	Au, Ag, Pb, Cu.	Breccia pipe	Granite gneiss	Hewett, 1956; Longwell and others, 1965.
Esmeralda County				
Alum	Alum, sulfur, Hg, gypsum	Vein	Rhyolite	Albers and Stewart, 1972; Lincoln, 1923; Spurr, 1906.
Black Horse	W, Mo Diatomite	Disseminated Contact metamorphic. Lacustrine	Tactite Tactite Lake beds	Albers and Stewart, 1972;
Buena Vista (Oneota, Basalt, Mount Montgomery).	Au, Ag, U W, Mo	Vein Contact	Phyllite, hornblende, diorite, andesitic tuff. Tactite, adamellite	Albers and Stewart, 1972; Lincoln, 1923; Ross, 1961.
Coaldale	Coal U	Bedded Veinlet, breccia pipe.	Lake beds Rhyolitic tuff	Duncan, 1953; Hance, 1913; Lincoln, 1923; Toenges and others, 1946.
Crow Springs	Au, Ag, Sb, Se, Cu, perlite.	Vein	Quartzite, chert	Albers and Stewart, 1972; Lawrence, 1963.

TABLE 3.—*Metallic mineral districts in the Death Valley region of Nevada*—Continued

Mining district	Commodities	Deposit type	Host rock	References
Esmeralda County—Continued				
Cuprite	Au, Ag, Cu, S	Vein Replacement	Limestone, rhyolite Rhyolitic tuff, limestone.	Ball, 1906, 1907; Ransome, 1909.
Divide (Gold Mountain).	Ag, Au, Mo	Vein	Rhyolite breccia	Knopf, 1921b; Lincoln, 1923; Schilling, 1962; Young, 1920.
Dyer	Ag, Pb, Cu	Vein	Slaty limestone	Lincoln, 1923; Spurr, 1906.
Fish Lake Marsh	Clay, B, U	Veinlet Bedded Disseminated	Lake beds Lake beds Tuffaceous rocks	Albers and Stewart, 1972; Lincoln, 1923; Smith, 1964.
Fish Lake Valley (White Mountain).	Hg, Sb	Fracture filling Veinlet Disseminated	Opalite, air-fall tuff, rhyolite, andesite, phyllite. Rhyolite Rhyolite	Holmes, 1965; Lawrence, 1963.
Gilbert (Desert)	Ag, Pb, Zn, Cu, Mo, W, Sb, Au.	Vein	Limestone, shale, chert, quartzite, rhyolite.	Ferguson, 1927.
Goldfield	Au, Ag, Cu, Pb, Bi, K, Sb, Sn, Te.	Vein	Rhyolite, dacite, andesite, tuff.	Ransome, 1909.
Goldfield Hills area.	Ba, Mn	Lens Vein Nodule	Cherty limestone Rhyolitic welded tuff Limestone	Albers and Stewart, 1972.
Good Hope (White Wolf).	Ag, Pb, Cu	Vein	Slate, quartzite	Albers and Stewart, 1972; Lincoln, 1923.
Hornsilver (Lime Point) Gold.	U, Ag, Au, Pb, Mo.	Vein	Limestone, shale	Albers and Stewart, 1972; Lincoln, 1923.
Klondyke (South Klondyke).	Au, Ag, Pb	Vein	Limestone	Spurr, 1906.
Lida (Alida, Tule Canyon).	Au, Ag, Pb, Cu.	Vein Placer	Limestone Gravel, sand, boulders	Root, 1909; Vanderburg, 1936.
Lone Mountain	Ag, Pb, Ba	Contact metasomatic.	Limestone, granite	Albers and Stewart, 1972; Ball, 1907; Lincoln, 1923;
West Divide (Weepah).	Au, Cu, Zn	Vein Replacement	Limestone Limestone	Oxnam, 1936; Stretch, 1904.
Montezuma	Au, Ag, Pb, Cu, Bi.	Vein Replacement	Limestone, shale Limestone, shale	Albers and Stewart, 1972; Lincoln, 1923; Stretch, 1904.
Palmetto	Au, Ag, Pb, Sb, Cu.	Vein	Alaskite, phyllite, sandstone, limestone.	Lawrence, 1963; Lincoln, 1923; Spurr, 1906.
Railroad Springs	Au, Ag, Cu	Vein	Limestone, shale	Albers and Stewart, 1972; Lincoln, 1923.
Red Mountain (Argentite).	Mn, Ag, Au, Pb, Zn, Cu.	Pipelike Vein	Tuffaceous beds Rhyolite, limestone, latite, sandstone.	Benson, 1950; Keith, 1977; Lincoln, 1923.
Rock Hill	Fe	Unknown		Reeves and others, 1958.
Silver Peak	Au, Ag, Cu	Lens	Alaskite, limestone schist.	Spurr, 1906.
Mineral Ridge	Pb	Vein Replacement	Dolomite, schist, quartzite, granite. Shaley limestone.	
Silver Peak Marsh	Lithium	Brine	Basin fill	Kunasz, 1971; Barrett and O'Neill, 1970; Norton, 1973.

TABLE 3.—*Metallic mineral districts in the Death Valley region of Nevada*—Continued

Mining district	Commodities	Deposit type	Host rock	References
Esmeralda County—Continued				
Sylvania (Green Mountain).	Mo, Re	Disseminated Vein	Quartz monzonite Marble	Albers and Stewart, 1972.
	Talc	Replacement	Dolomite	
Tokop (Gold Mountain, Oriental Wash, Bonnie Claire).	Au, Ag, Pb, Cu.	Vein	Slaty schist, granite	Ransome, 1907.
Tonopah	U, Clay	Disseminated Bedded	Tuff Tuffaceous beds	Albers and Stewart, 1972.
Windypah	Au, Ag, Cu, Pb, Ba, Sb.	Lens Vein Replacement	Alaskite Slaty limestone, granite Chert	Spurr, 1906.
Lincoln County				
Groom	Au, Ag, Pb, Zn, Cu.	Breccia zone Fissure/beds	Limestone, quartzite Pioche Shale	Tschanz and Pampeyan, 1970.
None	Ag, Pb, Cu	Shear zone	Limestone	Tschanz and Pampeyan, 1970.
Pahranagat (Hiko)	Ag, Pb, Cu, Mn, Au.	Vein	Limestone, dolomite	Tschanz and Pampeyan, 1970.
Papoose	Au, Ag, Pb	Fissure vein	Quartzite	Tschanz and Pampeyan, 1970.
Tem Piute	Ag, W, Mo	Contact metamorphic.	Tactite, limestone, shale.	Couch and Carpenter, 1943; Hill, 1916; Holmes, 1965; Lemmon and Tweto, 1962; Schilling, 1962; Schilling, 1963; Tschanz and Pampeyan, 1970.
	Zn, F, Bi, Hg, Pb.	Vein/replacement Fracture filling	Dolomite Andesite and rhyolite flow.	
Mineral County				
Bell (Simon, OMCO, Cedar Mountain).	Au, Ag, Pb, Zn, W, Hg, Cu.	Vein Replacement Contact metamorphic.	Volcanic rocks, limestone, andesite. Limestone Tactite, limestone, granite.	Bailey and Phoenix, 1944; Couch and Carpenter, 1943; Knopf, 1921a; Ross, 1961; Vanderburg, 1937b.
Nye County				
Antelope Springs	Au, Ag, Pb	Vein Disseminated	Rhyolite Tuff	Cornwall, 1972; Kral, 1951.
Ash Meadows	Clay	Sedimentary	Playa deposit	Cornwall, 1972; Kral, 1951.
Barcelona (Spanish Belt, Spanish).	Au, Ag, Pb, Zn, Sb, Hg, Se, Mo, Cu, F, U, W, Ti, Fe, V.	Vein Peneconcordant Contact metamorphic.	Shale, schist, granite, limestone. Ash-flow tuff Granite, skarn	Garside, 1973; Kleinhampl and Ziony, 1984.
Bellehelen	Au, Ag, V, Fe.	Vein Fissure filling	Tuff Welded tuff	Kleinhampl and Ziony, 1984; Kral, 1951.
Belmont (Philadelphia, Silver Bend).	Ag, Sb, Pb, Cu, W.	Vein	Carbonate rocks, granite porphyry.	Kleinhampl and Ziony, 1984.
Bruner (Phonolite).	Au, Ag	Vein	Rhyolite, andesite	Kleinhampl and Ziony, 1984; Kral, 1951.
Bullfrog (Pioneer, Rhyolite).	Au, Ag, Cu, U, Clay.	Replacement Vein	Rhyolite Rhyolite, limestone, tuff, shale.	Cornwall and Kleinhampl, 1964; Garside, 1973; Kral, 1951; Ransome and others, 1910.
Cactus Spring	Au, Ag, Cu	Vein	Rhyolite	Ball, 1907; Kral, 1951.

TABLE 3.—*Metallic mineral districts in the Death Valley region of Nevada*—Continued

Mining district	Commodities	Deposit type	Host rock	References
Nye County—Continued				
Clifford	Au, Ag	Vein	Rhyolitic tuff	Kleinhampl and Ziony, 1984; Kral, 1951.
Cloverdale (Golden, Black Springs).	Au, Cu, As, Be, F, Ag, Pb, Zn, Cd, Sb, Ba, Mn.	Placer Vein	Gravel Quartz latite,welded tuff, rhyolite.	Kleinhampl and Ziony, 1974; Kral, 1951; Papke, 1979; Vanderburg, 1936.
Ellendale	Au, Ag, Pb, Zn, Cu, Sb, Hg, Sn, Cd, Mn, Ba.	Vein Replacement Skarn	Rhyolite, andesite Limestone Metamorphic rocks	Kleinhampl and Ziony, 1984; Kral, 1951.
Ellsworth (Marble Falls).	Au, Pb, Sb, Zn.	Vein Replacement	Greenstone, volcanics, limestone, granite. Dolomite, shale, quartzite.	Kleinhampl and Ziony, 1984; Kral, 1951; Reeves and others, 1958.
Fairplay (Atwood, Goldyke).	Au, Ag, Pb W, Mo, Cu, Hg.	Contact metamorphic. Vein Disseminated	Tactite, granite Greenstone, andesite Limestone	Kleinhampl and Ziony, 1984; Kral, 1951.
Fluorine (Bare Mountain).	Au, F, U, Ag, W, Pb, Hg, marble, diatomaceous earth, stone, perlite, pumicite, silica.	Vein Replacement Breccia pipe	Schist, quartzite, sandstone, siltstone. Limestone, dolomite Dolomite	Cornwall and Kleinhampl, 1964; Garside, 1973; Kral, 1951; Papke, 1979.
Gabbs	Au, Ag, Pb, Fe, Cu, Mo, Mg, W.	Replacement Pipes Vein	Dolomite Limestone Shale, granodiorite	Callaghan, 1933; Kleinhampl and Ziony, 1984; Kral, 1951; Reeves and others, 1957; Vitaliano and Callaghan, 1956.
Gold Crater	Au, Ag, Pb, Cu.	Pipe	Biotite andesite	Ball, 1907; Kral, 1951.
Golden Arrow (Blakes Camp).	Au, Ag, Cu, Zn.	Vein Fracture filling	Andesite Pink rhyolite, andesite	Ferguson, 1917; Kral, 1951.
Hannapah (Volcano, Silverzone, Bannock).	Au, Ag	Vein	Volcanics, welded tuff, rhyolite.	Garside, 1973; Kleinhampl and Ziony, 1974 Kral, 1951.
Jackson (Gold Park).	Au, Ag, Pb, Cu, Hg, U, F.	Fissure filling Vein	Ash-flow tuff Meta-andesite, rhyolite.	Bonham, 1970; Garside, 1973; Kleinhampl and Ziony, 1984; Kral, 1951.
Jett (Argentore, Silver Point, Ledbetter Canyon, Peavine Canyon, Wall Canyon).	Au, Ag, Pb, Zn, Sb, Cu, Hg, W, As.	Vein Placer	Shale, limestone, schist. Gravel	Kleinhampl and Ziony, 1984; Kral, 1951; Lawrence, 1963.
Johnnie	Au, Pb, Cu, U	Vein Placer	Quartzite, limestone Gravel	Garside, 1973; Kral, 1951.
Lee (Big Dune)	Au	Vein	Dolomite	Cornwall, 1972.

TABLE 3.—*Metallic mineral districts in the Death Valley region of Nevada*—Continued

Mining district	Commodities	Deposit type	Host rock	References
Nye County—Continued				
Longstreet (Fresno, Georges Canyon).	Au, Ag, Pb, Zn, Hg.	Gossan, vein. Placer	Rhyolitic tuff Gravel	Kleinhampl and Ziony, 1984; Kral, 1951.
Manhattan	Au, Ag, Pb, Cu, Mo, Sb, F, As, Ba.	Replacement Vein	Limestone Limestone, andesite porphyry schist, sandstone, quartite.	Ferguson, 1924; Kral, 1951; Papke, 1979.
Mellan Mountain	Au, Ag	Vein	Rhyolitic ash-flow tuff	Cornwall, 1972; Kral, 1951.
Mine Mountain	Ag, Pb, Hg	Vein	Quartzite, dolomite	Cornwall, 1972.
Oak Springs (Climax).	Au, Ag, Pb, W, Mo.	Vein Contact metamorphic.	Limestone, shale Limestone, quartz monzonite.	Kral, 1951.
Republic area	Ag, Pb, Au Zn.	Vein	Rhyolite, limestone	Kleinhampl and Ziony, 1984; Kral, 1951.
Royston Hills area.	Au, Ag, Pb, Cu.	Vein	Chert, andesite	Kleinhampl and Ziony, 1974; Kral, 1951.
San Antone (Cimarron, San Antonio).	Au, Ag, Pb, Cu, Mo.	Epithermal Vein Replacement	Rhyolite, latite Shale, limestone, quartzite, quartz mica schist. Rhyolite	Kleinhampl and Ziony, 1984; Kral, 1951.
Silverbow	Au, Ag	Vein	Rhyolitic tuff	Kral, 1951.
Stonewall	Au, Ag	Vein	Rhyolitic welded tuff, quartz latite.	Ball, 1907; Cornwall, 1972; Kral, 1951; Lincoln, 1923.
Tolicha (Monte Cristo, Clarkdale).	Au, Ag	Vein	Rhyolitic ash-flow tuff.	Kral, 1951.
Tonopah	Au, Ag, U	Vein Disseminated	Trachyte, tuff, rhyolite dacite. Tuffaceous lake beds	Garside, 1973; Spurr, 1905.
Trappmans	Au, Ag	Vein	Quartz monzonite, schist.	Ball, 1906, 1907.
Tybo, (Hot Creek, Empire, Keystone).	Au, Ag, Pb, Zn, Mo, Cu. Hg, Sb, Cd Mn, Se, Fe, As, Ba.	Replacement Disseminated Vein Pods	Limestone, shale Tuff Limestone, rhyolitic tuff. Dolomite	Ferguson, 1933; Horton, 1963; Kleinhampl and Ziony, 1974; Kral, 1951; Lawrence, 1963.
Union (Berlin Ione, Grantsville).	Au, Ag, Pb, Zn, Cu, Hg, Sb, Se, F, W.	Vein Replacement Placer	Rhyolite, greenstone, clastics, limestone. Limestone Gravel	Kral, 1951; Kleinhampl and Ziony, 1984; Papke, 1979.
Wahmonie	Au, Ag, Cu	Vein	Latite, dacite, tuff, breccias, quartzite.	Cornwall, 1972; Kral, 1951.
Wellington (Jamestown, O'Briens).	Au, Ag, Cu	Vein	Rhyolitic ash-flow tuff.	Ball, 1906; Kral, 1951.
Wilsons	Au, Ag	Vein	Rhyolitic ash-flow tuff.	Kral, 1951.

TABLE 4.—*Metallic mineral districts of the Death Valley region of California*

[Meridian names are abbreviated as follows: MD, Mount Diablo; SB, San Bernardino. Commodities listed in the commodities column are abbreviated as follows: Ag, silver; As, arsenic; Au, gold; Ba, barium; Cu, copper; F, fluorine; Fe, iron; Hg, Mercury; Mn, manganese; Mo, molybdenum; Pb, lead; Sb, antimony; Sn, tin; Sr, strontium; W, tungsten; Zn, zinc. These data are from Wong (1983a), and they are preliminary and subject to revision]

Mining district	Commodities	Deposit type	Host rock	References
Inyo County				
Argus (Kelley)	Au, Ag, Fe, Cu.	Vein	Granite, diorite, andesite.	Clark, 1970; Norman and Stewart, 1951.
Ballarat-South Park.	Au	Vein	Schist, dolomitic limestone, gneiss.	Clark, 1970; Norman and Stewart, 1951.
Beveridge	Au, Ag, Cu, Pb, Zn, Fe.	Vein	Granite, quartz monzonite, limestone quartzite, schist.	Norman and Stewart, 1951.
Cerro Gordo	Au, Ag, Cu, Pb, Zn.	Vein Replacement	Limestone, slate Limestone	Goodwin, 1957; Norman and Stewart, 1951.
Chidago	Au, Ag, Pb, Fe.	Vein	Limestone	Goodwin, 1957; Norman and Stewart, 1951.
Chloride Cliff (South Bullfrog).	Au, Ag, Pb, Cu.	Vein	Limestone,schist, quartzite.	Clark, 1970; Goodwin, 1957; Norman and Stewart, 1951.
Darwin (Coso)	Ag, Pb, Zn, Au, Cu, As, W, Sb, F, Fe.	Vein Replacement	Limestone, tactite, calc-hornfels. Limestone	Goodwin, 1957; Hall and MacKevett, 1962; Norman and Stewart, 1951.
Deep Spring	Ag, Cu	Vein	Granite	Goodwin, 1957; Waring and Huguenin, 1919.
Echo Canyon-Lees Camp.	Au	Vein	Metamorphic rocks	Clark, 1970; Norman and Stewart, 1951.
Grapevine	Au	Vein	Metamorphosed sedimentary rocks.	Clark, 1970.
Greenwater	Cu	Unknown		Eric, 1948; Waring and Huguenin, 1919.
Harrisburg	Au	Vein	Dolomitic limestone	Clark, 1970; Norman and Stewart, 1951; Waring and Huguenin, 1919.
Lee	Au, Ag, Pb, Zn, Cu.	Vein	Limestone	Norman and Stewart, 1951.
Modoc	Au, Ag, Pb	Vein Replacement	Granitic rocks, schist, limestone. Limestone	Clark, 1970; Goodwin, 1957; Norman and Stewart, 1951.
Old Coso	Au, Ag, Cu, Hg	Vein	Granite	Norman and Stewart, 1951.
Panamint	Cu, Ag	Vein	Schist, limestone	Goodwin, 1957.
Pine Mountain	Au, Ag, Pb, Cu	Vein Replacement	Schist Limestone, schist	Norman and Stewart, 1951.
Resting Spring	Pb, Zn	Replacement(?)	Dolomite	Goodwin, 1957.
Saratoga	Au, Ag, Pb, Zn, Cu.	Replacement	Limestone	Goodwin, 1957.
Skidoo-Tucki Mountain.	Au	Vein	Quartz monzonite	Clark, 1970; Norman and Stewart, 1951.
Slate Range (Daily Dozen mine).	Au, Ag	Fissure vein	Granite, quartz monzonite.	Smith and others, 1968.
Tibbets (Union)	Au, Ag, Pb Cu, W, Mo, Fe	Contact metamorphic. Vein	Quartz monzonite, limestone. Granite, limestone	Goodwin, 1957; Lemmon and Tweto, 1962.

TABLE 4.—*Metallic mineral districts in the Death Valley region of California*—Continued

Mining district	Commodities	Deposit type	Host rock	References
Inyo County—Continued				
Ubehebe	Au, Ag, Pb, Cu, W.	Vein Contact metasomatic.	Granite, limestone	Clark, 1970; Walker and others, 1956.
Wild Rose	Au, Ag, Cu, Pb, Sb, Zn.	Placer Vein Replacement	Gravel Schist, gneiss, granitic rocks. Limestone	Clark, 1970; Norman and Stewart, 1951; White, 1940.
Willow	Au, Cu	Vein	Gneiss, schist	Clark, 1970; Norman and Stewart, 1951.
Mono County				
White Mountains area.	Au, Ag, Pb Cu, W.	Placer Vein	Gravel Granitic rocks, schist, limestone, slate, hornfels.	Goodwin, 1957; Sampson and Tucker, 1940.
San Bernardino County				
Avawatz Mountain area.	Au, Ag, Cu, Pb, Zn, Fe, Sr.	Contact	Limestone	Wright and others, 1953.
Clark (Clark Mountain).	Au, Cu, W, Pb, Ag, Zn.	Vein	Gneiss, quartz monzonite, limestone.	Clark, 1970; Wright and others, 1953.
Goldstone	Au, Cu, Ag	Vein	Limestone, shales, diorite, dike, schist.	Clark, 1970; Wright and others, 1953.
Halloran Springs	Au, Cu, Ag, Pb, Fe.	Vein	Quartz monzonite, basalt, granite.	Clark, 1970; Wright and others, 1953.
Homer Mountain area	Pb, Ag, Cu	Vein	Unknown	Wright and others, 1953.
Ibex	Au, Mn, Cu	Vein	Gneiss, schist	Wright and others, 1953.
Ivanpah (Bullion, Koko Weef, Mescal).	Au, Ag, Pb Cu, Zn, Fe, W, Sn.	Vein Contact metasomatic.	Limestone, quartz monzonite. Limestone, quartz monzonite.	Lemmon and Tweto, 1962; Wright and others, 1953.
Kingston Range area	Au, Ag, Pb, Zn, Cu, Fe.	Contact	Dolomite, limestone, amphibolite.	Wright and others, 1953.
Morrow	Au, Cu	Vein	Granite, limestone	Wright and others, 1953.
Mountain Pass	Rare earths, Cu, Pb, F, Mo, Zn, Ag, Sb, Ba.	Vein	Gneiss, shonkinite-syenite.	Olson and others, 1954.
Owlshead	Mn	Fissure filling. Vein	Brecciated limestone, granite, fanglomerate. Granite, marble	Davis, 1957; Mann, 1916; Trask, 1950.
Sacramento Mountain area.	Au, Ag, Cu, Fe, Hg.	Vein	Gneiss, granite	Wright and others, 1953.
Shadow Mountains	Au, Ag, Pb, Cu.	Vein	Granitic gneiss	Clark, 1970; Wright and others, 1953.
Slate Range (Sandora, Early Spring, Johnson mine).	Au Ag, Pb Au	Vein Vein Vein, dike	Quartz monzonite Mesozoic metavolcanics, shale. Mesozoic metavolcanics.	Smith and others, 1968.
Soda Mountains area	Au, Ag, Cu	Vein	Granite	Wright and others, 1953.
Vanderbilt (New York).	Au, Ag, Pb, Cu, Zn.	Vein	Gneiss, pegmatite dike, granite, dolomite.	Clark, 1970; Wright and others, 1953.

metamorphosed sediments of the Precambrian Wyman Formation (Albers and Stewart, 1972). These gold-bearing ore shoots, which also contain some silver, are related to a Late Jurassic or Early Cretaceous alaskite intrusive. More than 311 Mg of silver (Kleinhampl, 1964) and at least 18 Mg of gold (Bergendahl, 1964) were produced from mines in the Silver Peak district. The Manhattan district contains vein deposits in Cambrian(?) limestone and quartz schist in the hanging wall section of an extensive northwest-trending thrust fault (Ferguson, 1924). Thin discontinuous gold-quartz veins are also present in Tertiary volcanic rocks in the Manhattan district; however, the lodes in the Paleozoic rocks have been the most productive. Lode ores at Manhattan have yielded more than 8.7 Mg of gold and at least 3.1 Mg of silver, and placer deposits in the district have produced an additional 6.2 Mg of gold (Bergendahl, 1964).

Precious metals were produced from the majority of the districts in the Death Valley region in Nevada. At least 3.1 Mg of gold were mined from ores in the Bullfrog, Ellendale, Johnnie, Tybo, and Union districts of Nye County, the Bell district of Mineral County, and the Eldorado, Goodsprings and Searchlight districts of Clark County (Bergendahl, 1964). Silver production exceeded 31.1 Mg from ores in the Goodsprings and Eldorado districts of Clark County, the Belmont and Tybo districts of Nye County, and the Divide district of Esmeralda County (Kleinhampl, 1964).

Many mineral deposits in the Death Valley region of California contain gold, but none of these deposits have recorded production comparable to similar deposits in Nevada. Gold concentrates valued at more than $1 million were produced from mesothermal quartz veins in the Ballarat–South Park, Chloride Cliff, and Skidoo–Tucki Mountain districts of Inyo County, Calif. (Clark, 1970). At least 248.8 Mg of silver were produced from Darwin district until 1951 (Hall and MacKevett, 1962), and more than 155.5 Mg of silver came from mines in the Cerro Gordo district, Inyo County (Stager, 1966).

The principal production of base metals to date in the Death Valley region has come from the Goodsprings district of Clark County and the Tem Piute district of Lincoln County, Nevada; and from the Darwin, Cerro Gordo, Saratoga, and Lee districts of Inyo County, Calif. Ore minerals of lead and zinc have been the principal sources of profits in these districts, whereas tungsten and byproduct silver are locally of special importance. Excluding the significant gold deposits near Goldfield, copper is of secondary importance in the majority of the base-metal deposits in the Death Valley region. The base-metal deposits in the Death Valley study area are mostly replacement deposits in faulted Paleozoic carbonate rocks. Silicic to intermediate intrusive rocks are common in many areas containing mineralized rocks. The mineral deposits at Darwin were developed continuously for long periods, whereas mining activities in the remaining base-metal districts generally were of short duration. Oxidation was extensive in many of the base-metal deposits, and much of the near-surface high-grade ore in these areas has been removed.

The Goodsprings district in Clark County has been an important source of zinc in Nevada. Deposits of several metals occur at Goodsprings, and zinc ores with associated lead have accounted for the bulk of the value and tonnage of all metals produced to date. The majority of the mineral deposits at Goodsprings are mantos, commonly occurring in the Upper Mississippian Yellowpine Member of the Monte Cristo Limestone (Hewett, 1931). The ores are related to granitic intrusives, and are commonly oxidized. Mines at Goodsprings produced more than $31 million in metals until 1962 (Longwell and others, 1965).

The Lincoln mine in the Tem Piute district was a major source of tungsten in Nevada between 1940 and 1957, and the area was also productive from 1975 to 1981. About 287,000 20-pound units of tungsten trioxide were produced during this period as part of a federally subsidized stockpile program (Tschanz and Pampeyan, 1970). Silver and small quantities of zinc and lead were mined as byproducts. The principal deposits at Tem Piute were elongated zones in tactites in Devonian and Mississippian limestones.

The principal sources of base metals in the Death Valley region of California are replacement or open-space filling deposits in faulted Paleozoic carbonate rocks. These deposits commonly are similar to nearby silicic to intermediate intrusive rocks. The mines in the Darwin district, Inyo County, historically have been an important source of lead in California (Norman and Stewart, 1951). Large quantities of silver and zinc also have been mined as coproducts at Darwin. At least $25 million worth of base and precious metals were mined at Darwin by 1953 (Carlisle and others, 1954). More than $17 million in lead-silver ore was produced from the Cerro Gordo district, principally before 1877 (Norman and Stewart, 1951). About 10,058 Mg of oxidized zinc ore was mined from cavity-filling deposits at Cerro Gordo, mainly between 1912 and 1919 (Carlisle and others, 1954).

The Shoshone mines in the Saratoga district and the Santa Rosa mine in the Lee district produced smaller, although still important, values and tonnages of base metals. These deposits are in fault-controlled silicified Paleozoic carbonate rocks.

In addition to the principal base and precious metals mentioned in the preceding discussion, many other metallic elements occur in variable quantities in the

Death Valley region. Some of the more common metals include arsenic, antimony, beryllium, bismuth, iron, manganese, mercury, molybdenum, and uranium. Substantial quantities of these elements have been produced only locally from a few mines in the study area to date. In contrast, one of the largest identified concentrations of rare-earth elements in the world occurs in the Death Valley region, near Mountain Pass, San Bernardino County, Calif. Large bastnaesite-bearing carbonate orebodies, and several hundred rare-earth vein deposits are associated with potash-enriched intrusives of the Mountain Pass mineral district (Olson and others, 1954). This deposit currently is the largest domestic source of rare-earth elements (Carrillo and others, 1983).

INDUSTRIAL MINERAL RESOURCES

Several varieties of nonmetallic industrial minerals and rocks are located in the Death Valley region. Many of these commodities have been produced intermittently and shipped to local markets. Deposits of semiprecious and precious gemstones, natural aggregates, and building stone are not discussed in this report. Overviews of the occurrences of the principal industrial rocks and minerals including construction materials are contained in reports by the U.S. Geological Survey (1964, 1966). Detailed commodity discussions occur in several reports published by the California Division of Mines and Geology and the Nevada Bureau of Mines and Geology.

Magnesite, brucite, fluorspar, and barite are the principal nonmetallic or industrial commodities with significant production in the Death Valley region within Nevada. Magnesite and brucite are mined currently near Gabbs in northwestern Nye County. This deposit is one of two presently active domestic magnesium mines, and these deposits are among the more important nonmetallic mineral occurrences in the study area. The replacement deposite at Gabbs occurs in dolomite of the Upper Triassic Luning Formation (Callaghan, 1933). The locally recrystallized host rocks are part of the upper plate of the Paradise thrust fault and have been intruded by numerous dikes and a Cretaceous granodiorite stock (Martin, 1956). The magnesite ore zones are satellitic around an extension of the granodiorite stock, while the principal brucite deposits are in contact with the intrusive (Vitaliano and Callaghan, 1956, 1963; Vitaliano and others, 1957). Several million metric tons of ore containing less than 5 percent admixed calcium oxide were mined prior to 1968. These deposits contained estimated reserves of at least 23 million Mg of high-grade ore in 1968 (Schilling, 1968).

Several deposits of fluorspar are in the Bare Mountain or Fluorine district, southern Nye County, Nev. The Daisy mine has been the principal source of metallurgical-grade fluorspar in the district. Between 1919 and 1976, at least 172,482 Mg of fluorspar were produced from the Daisy mine (Papke, 1979) where it occurs as fracture-fillings in dolomite of the Upper Cambrian Nopah Formation (Thurston, 1949; Cornwall and Kleinhampl, 1964). Smaller although productive breccia pipe and fissure deposits containing fluorspar occur on the eastern side of Bare Mountain; workings here include the Mary and Goldspar mines. The Mary mine has yielded an estimated 11,800 Mg of fluorspar averaging 40 percent calcium fluoride. About 68,085 Mg of 40-percent calcium fluoride-bearing ore came from the Goldspar mine (Papke, 1979).

Barite occurrences are abundant in the Death Valley region of Nevada; however, only the Jumbo mine in the Ellendale district in central Nye County has produced more than 9,000 Mg of ore (Horton, 1964). Substantial quantities of manganese oxide have been produced at the Three Kids mine in the area north of Boulder City (Hewett and Webber, 1931).

Talc is the principal industrial mineral of known importance in the Death Valley region of California. California historically has been an important domestic source of steatite. The majority of the high-grade talc deposits in the California part of the study area occur in a zone that extends for about 121 km through southern Death Valley eastward to the Kingston Range in northeastern San Bernardino County (Wright, 1964). These talc deposits commonly are irregular and lenticular bodies located near the contacts between diabase sills and silicified carbonate rocks of the Precambrian Crystal Spring Formation. The host rocks are intensely deformed, and faulting is common in the weak talc-bearing horizons. The majority of the talc mines in the area are developed from 1,305 m to 1,524 m along the outcrop, and to depths less than 152 m (Wright, 1964). More than 1 million metric tons of talc-bearing material had been produced from the mines in the southern Death Valley–Kingston Range region by 1959 (Wright, 1968).

Brines pumped from beneath the surface of the dry lake in the Silver Peak Marsh district, central Esmeralda County, Nev., are currently an important world source of lithium. The playa sediments contain abundant hectorite and are saturated with brine to depths of 183–451 m (Kunasz, 1971). These brines, which contain about 300 mg/L lithium (Barrett and O'Neill, 1970), are evaporated to produce a concentrated product for shipment. The well field at Silver Peak Marsh has supplied very large quantities of lithium since 1966 (Norton, 1973); however, no production statistics are available at present.

Borates in the Death Valley region of Nevada occur as bedded Tertiary deposits and as marsh deposits containing mostly ulexite. Colemanite, ulexite, and probertite locally are abundant in folded Tertiary lakebeds near Furnace Creek in Death Valley and in the Amargosa Valley, Inyo County, Calif. (Ver Planck, 1950; McAllister, 1970; 1973). A large colemanite deposit occurs in the area of Callville Wash, about 42 km east of Las Vegas, which was developed by two adits and 2,134 m of underground workings. About 181,560 Mg of colemanite that averaged 20 percent B_2O_3 were produced from the Callville Wash deposit between 1921 and 1928 (Vanderburg, 1937a). Bedded ulexite was mined as late as 1939 from deposits east of Fish Lake Valley, Esmeralda County (Smith, 1964). Ulexite was mined from marsh deposits from 1870 to 1892, many of which are in the Death Valley region.

Extensive gypsum deposits occur in Permian rocks along the eastern slope of the Spring Mountains west and southwest of Las Vegas. The estimated annual production during 1965 was 272,340 Mg (Longwell and others, 1965). Large gypsum resources also exist in Permian and Tertiary strata in the southern end of Frenchman Mountain, central Clark County. Annual production from this area was estimated by Longwell and others (1965) to be 90,780 Mg.

Besides borates, the principal saline minerals in the Death Valley region of California are halite and gypsum. Production of evaporite minerals from playa deposits has been small and of short duration; however, large resources of saline minerals are identified locally. Salt beds, as thick as 6 m, and interbedded lacustrine clays were penetrated to a depth of about 305 m near Badwater in Death Valley (Bain, 1914; Gale, 1914). Tertiary lake beds in the Avawatz Range area are reported to contain about 1.2 million Mg of salt within about 50 m of the surface (Ver Planck, 1958). In addition, near-surface deposits of gypsum occur near Tecopa (Withington, 1966) and in the Avawatz Range area (Ver Planck, 1958).

GEOTHERMAL RESOURCES

There are currently two Known Geothermal Resource Areas (KGRA) in the Death Valley region. The Saline Valley KGRA has an area of 1,295 ha in T. 13 S., R. 39 E., Inyo County, Calif., and the Silver Peak KGRA has an area of 2,071 ha in T. 2. S., R. 39 E., Esmeralda County Nev. (U.S. Bureau of Land Management, 1983a, b). These lands are classified as such based on formal determination by the Bureau of Land Management of competitive interest in the lands (Burkhardt and others, 1980). Competitive interest, as defined in Title 43, Chapter II of the Code of Federal Regulations, subpart 3200.0.5 (k)(3), exists "***in the entire area covered by an application for a geothermal lease if at least one-half of the lands covered by that application are also covered by another application which was filed during the same application filing period." The total area in the Saline Valley KGRA is covered by Federal competitive interest, and 2,055 Federal competitive hectares are in the Silver Peak KGRA (Burkhardt and others, 1980). The Saline Valley and Silver Peak KGRAs both contain hot springs, and these areas are characterized further by warm surface temperatures of 65 °C and 48 °C, respectively (Burkhardt and others, 1980). The temperature range for the Saline Valley area geothermal reservoir is estimated to be between 65 °C and 96 °C (Burkhardt and others, 1980). These data are projected from well temperatures or chemical geothermometry. No similar data currently are available for the geothermal reservoir near Silver Peak.

Geothermal waters within 915 m of the surface, with temperatures sufficient for direct heat application, occur north of Tecopa and along Furnace Creek Wash in Inyo County, Calif. (Higgins, 1980). These geothermal occurrences along Furnace Creek Wash in the Death Valley region are known to have temperatures greater than 50 °C. An oil-test hole was drilled by Nevada Oil and Minerals in 1970 at Fish Lake Valley, Esmeralda County, Nev., to a depth of 2,798 m. The bottom-hole temperature of this well was recorded on a temperature log at 158 °C (Garside and Schilling, 1979). Alkali Springs, 16 km northwest of Goldfield, Esmeralda County, have produced water of at least 60 °C (Ball, 1907). In addition, springs in the Black Canyon of Nevada and Arizona yield warm water with temperatures as great as 62 °C (Garside and Schilling, 1979). More than 50 thermal wells and 40 warm springs occur in the Death Valley region; however, the majority of the temperatures in these wells and springs are between 20 °C and 35 °C.

COAL, OIL, AND GAS RESOURCES

The only known coal-bearing strata in the Death Valley region are in the Coaldale field, Esmeralda County, Nev. Thin bituminous coals, commonly 1–2.1 m thick, occur at four horizons in moderately tilted and extensively faulted interbedded Tertiary shale, sandstone, bentonite, and tuff (Andrews and others, 1947; Hance, 1913). The Coaldale field has produced a very small tonnage of coal. There are currently no known oil or gas fields or producing hydrocarbon wells in the Death Valley region, though at least 60 dry holes have been drilled to date in the study area (Brady, 1983). Historically, the greatest effort in the search for hydrocarbons in the Death Valley region has been focused on

Paleozoic rocks in the Las Vegas Valley. Several very deep boreholes have been completed in this area, but none of the holes produced appreciable quantities of oil or gas.

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