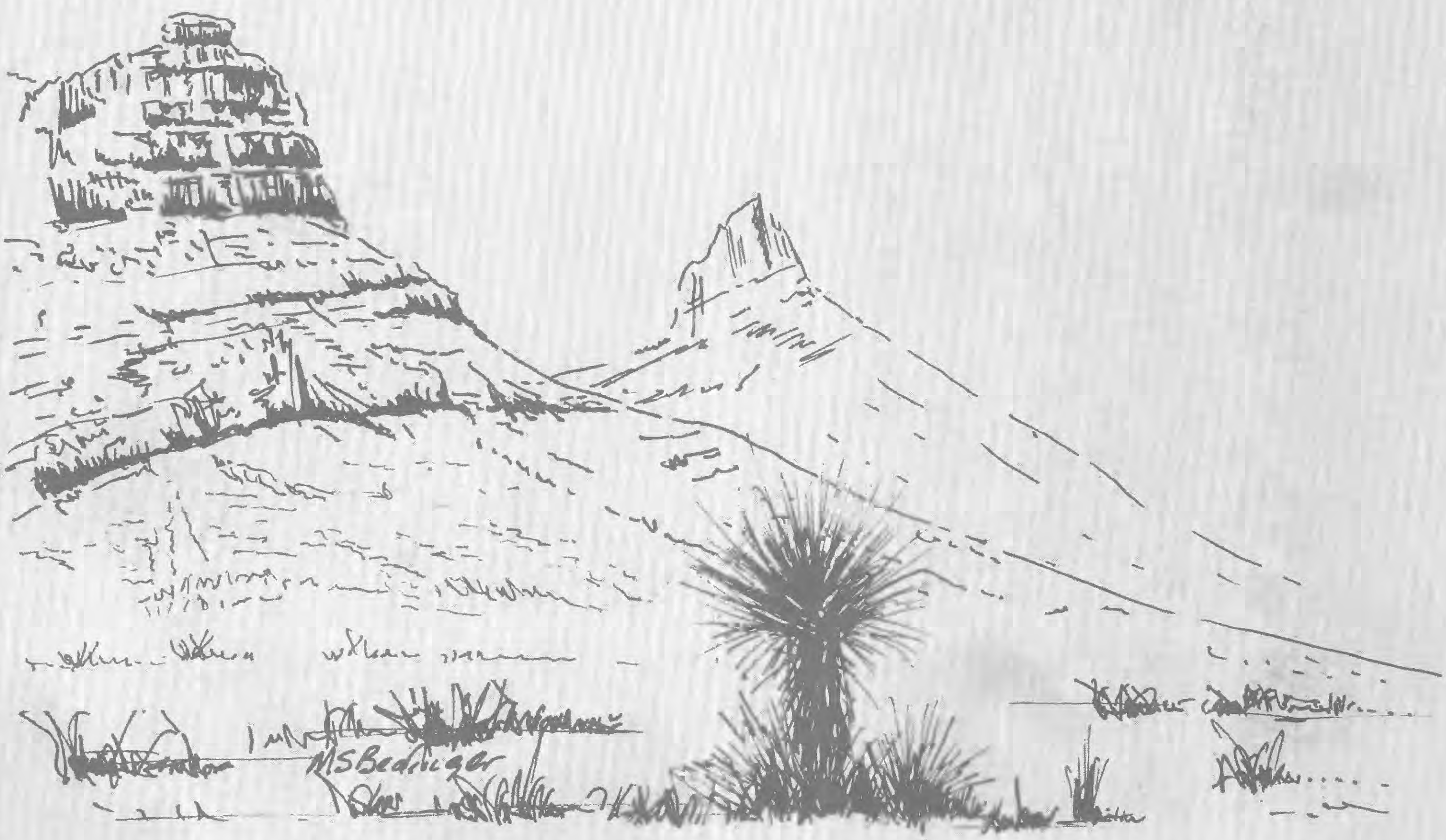
Studies of Geology and Hydrology in the Basin and Range Province, Southwestern United States, For Isolation of High-Level Radioactive Waste—Characterization of the Sonoran Region, California

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1370-E

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



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

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

STUDIES OF GEOLOGY AND HYDROLOGY FOR ISOLATION OF HIGH-LEVEL RADIOACTIVE WASTE

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1370-E

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

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1989

DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., *Secretary*

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging-in-Publication Data

Studies of geology and hydrology in the Basin and Range province, southwestern United States, for isolation of high-level radioactive waste—characterization of the Sonoran region, California

(U.S. Geological Survey professional paper ; 1370-E)
"Prepared in cooperation with the States of Arizona, California, Idaho, Nevada, New Mexico, Texas, and Utah."
Includes bibliographies.
Supt. of Docs. no.: I 19.16:1370-E
1. Geology—California, Southern. 2. Geology—Sonoran Desert. 3. Water, Underground—California, Southern. 4. Water, Underground—Sonoran Desert. 5. Radioactive waste disposal in the ground—California, Southern. 6. Radioactive waste disposal in the ground—Sonoran Desert. I. Bedinger, M.S. II. Sargent, Kenneth A. III. Langer, William H. IV. Series.
QE90.S63S78 1989 557.94'.9 86-600322

For sale by the Books and Open-File Reports Section, U.S. Geological Survey, Federal Center, Box 25425, Denver, CO 80225

BASIN AND RANGE PROVINCE WORKING GROUP

U.S. Geological Survey Members

Chairman of the Province Working Group:
M.S. Bedinger, Hydrologist
U.S. Geological Survey
Denver, CO

Member:
K.A. Sargent, Geologist
U.S. Geological Survey
Denver, CO

State Members and Alternates

ARIZONA

Member:
Larry D. Fellows
State Geologist and Assistant Director
Arizona Bureau of Geology and Mineral Technology
Tucson, AZ

Alternate:
H. Wesley Peirce
Principal Geologist
Arizona Bureau of Geology and Mineral Technology
Tucson, AZ

CALIFORNIA

Member:
Robert Streitz
Geologist
California Division of Mines and Geology
Sacramento, CA

IDAHO

Member:
Frank B. Sherman
Chief, Ground-Water Section
Idaho Department of Water Resources
Boise, ID

Alternate:
Darrel Clapp
Chief, Technical Services Bureau
Idaho Department of Water Resources
Boise, ID

NEVADA

Member:
John Schilling
State Geologist
Nevada Bureau of Mines and Geology
University of Nevada, Reno
Reno, NV

Alternate:
Susan L. Tingley
Deputy to the State Geologist
Nevada Bureau of Mines and Geology
University of Nevada, Reno
Reno, NV

NEW MEXICO

Member:
James M. Hill
Chief, Bureau of Geology
New Mexico Energy and Minerals Department
Santa Fe, NM

Alternate:
Frank E. Kottlowski
Director
New Mexico Bureau of Mines and Geology
Socorro, NM

TEXAS

Member:
Christopher D. Henry
Geologist
Texas Bureau of Economic Geology
University of Texas at Austin
Austin, TX

Alternate:
Douglas Ratcliff
Associate Director
Texas Bureau of Economic Geology
University of Texas at Austin
Austin, TX

UTAH

Member:
Genevieve Atwood
State Geologist
Utah Geological and Mineral Survey
Salt Lake City, UT

Alternate:
Don R. Mabey
Senior Geologist
Utah Geological and Mineral Survey
Salt Lake City, UT

CONTENTS

	Page
Abstract	E1
Introduction, by M.S. Bedinger, K.A. Sargent, and George I. Smith	2
Background and purpose	2
Geographic setting	2
Acknowledgments	3
References cited	4
Geology, by George I. Smith and Robert Streitz	5
Stratigraphy	5
Precambrian metamorphic rocks	5
Precambrian and lower and middle Cambrian sedimentary rocks	6
Middle Cambrian through middle Paleozoic sedimentary rocks	6
Upper Paleozoic sedimentary rocks	6
Lower Mesozoic metasedimentary and metavolcanic rocks	7
Upper Mesozoic plutonic rocks	8
Oligocene and Miocene sediments	8
Oligocene and Miocene volcanic rocks	8
Pliocene and lower Quaternary sediments	9
Upper Quaternary sediments and alluvium	9
Upper Quaternary volcanic rocks	10
Structure	10
Geomorphology	11
References cited	12
Potential host media for radioactive waste, by K.A. Sargent	15
Intrusive rocks	15
Tuffaceous rocks	16
Basaltic rocks	16
Potential host media for radioactive waste—Continued	
Evaporite deposits	E16
Unsaturated zone	16
References cited	16
Quaternary tectonism, by K.A. Sargent and George I. Smith	17
Seismicity	17
Heat flow	17
Quaternary faulting	17
Late Cenozoic volcanic rocks	17
Vertical crustal movement	17
Photolineations	17
References cited	17
Ground-water hydrology, by M.S. Bedinger, William H. Langer, and J.E. Reed	20
Major hydrogeologic units	20
Ground-water flow regime	20
Ground-water flow analysis	21
Areal ground-water flow	21
Cross-sectional models	21
Quality of ground water	22
Pleistocene hydrologic conditions	22
References cited	25
Mineral and energy resources, by B.T. Brady	26
Metallic mineral resources	26
Nonmetallic mineral resources	28
Evaporite deposits	29
Geothermal resources	29
Coal and oil resources	29
References cited	29

ILLUSTRATIONS

[Plates are in pocket]

PLATE 1. Map showing physiographic features of the Sonoran region, California.
2. Geologic sections, Sonoran region, California.
3. Map showing potential host rocks and areas of thick unsaturated zones, Sonoran region, California.
4. Map showing hydrogeologic units and relative velocities of ground water at the water table, Sonoran region, California.
5. Map showing relative ground-water traveltimes and flow paths at the water table and natural discharge areas, Sonoran region, California.
6. Hydrogeologic sections *A–A′*, *B–B′*, *C–C′*, and *D–D′* showing ground-water flow paths and relative traveltime, Sonoran region, California.
7. Map showing general location of the principal mining districts, Sonoran region, California.

	Page
FIGURE 1. Map showing major geographic features in the Sonoran region, California, and vicinity	E3
2. Map showing possible limits of areas underlain by detachment faults and eastern limit of Quaternary lateral faulting in the Sonoran region and vicinity, and ground-water units within the region	7
3. Map showing Quaternary tectonic features in the Sonoran region and vicinity	18
4. Photograph of part of the Cima volcanic field	19
5. Map showing dissolved-solids concentration of ground water	23
6. Map showing distribution of chemical types of ground water	24

TABLES

Page

TABLE 1. Hydraulic properties of hydrogeologic units and hydraulic gradients used in estimating relative ground-water velocities at the water table E21

2. Hydraulic properties of hydrogeoloic units used in cross-sectional models 22

3. Metallic mineral districts 27

CONVERSION FACTORS

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

Multiply SI unit	*By*	*To obtain U.S. customary unit*
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic hectometer (hm^3)	810.7	acre-foot (acre-ft)
liter (L)	0.2642	gallon (gal)
	Flow	
liter per minute (L/min)	0.2642	gallon per minute (gal/min)
	Temperature	
degree Celsius (°C)	9/5 (°C) + 32 = °F	degree Fahrenheit (°F)
	Mass	
kilogram	2.205	pound, avoirdupois (lb)
megagram (Mg) or metric ton	1.102	short ton (2,000 lb)
	Chemical Concentration	
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 SONORAN REGION, CALIFORNIA

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

ABSTRACT

The Sonoran region of California lies west of the Colorado River and adjoins the Mojave Desert on the west, Death Valley on the northwest, and the Salton trough on the south. The region is arid with annual precipitation ranging from less than 80 millimeters to as great as 250 millimeters in one mountain range; annual free-surface evaporation is as great as 2,500 millimeters. The characteristic basin and range topography of the region was caused by a mid-Tertiary period of intense crustal extension, accompanied by volcanic eruptions, clastic sedimentation, faulting, and tilting. Potential host media for isolation of high-level radioactive waste include granite and other coarse-grained plutonic rocks, ash-flow tuff, and basalt and basaltic andesite lava flows. Thick sections of the unsaturated zone in basin fill, intrusive, and volcanic rocks appear to have potential as host media. The region is bordered on the west by areas of relatively greater Quaternary faulting, vertical crustal uplift, and seismicity. The region has a few areas of Quaternary volcanic activity. Geothermal heat flows of 2.5 heat-flow units or greater and one earthquake of magnitude 6–7 have been recorded.

The region includes topographically closed basins as well as basins that drain to the Colorado River. Dry lakes and playas occupy the closed basins. Ground-water recharge and surface runoff are small because of the small amount of precipitation and great potential evaporation. Natural ground-water discharge is by evaporation in the basin playas and by underflow to the Colorado River. Dissolved-solids concentration of ground water generally is less than 500 milligrams per liter, and much of it is of the sodium bicarbonate type. Ground water is saline in many of the playas, and chloride or sulfate is the predominant anion. Small tonnages of ore have been produced from numerous precious and fewer base-metal deposits.

Manuscript approved for publication February 12, 1985.

INTRODUCTION

By M.S. Bedinger, K.A. Sargent, and George I. Smith

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 this Professional Paper (Bedinger, Sargent, and others, 1989). The evaluation of the regions is given in Chapter H (Bedinger, Sargent, and Langer, 1989). The titles of chapters in this series are:

- **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

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

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

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

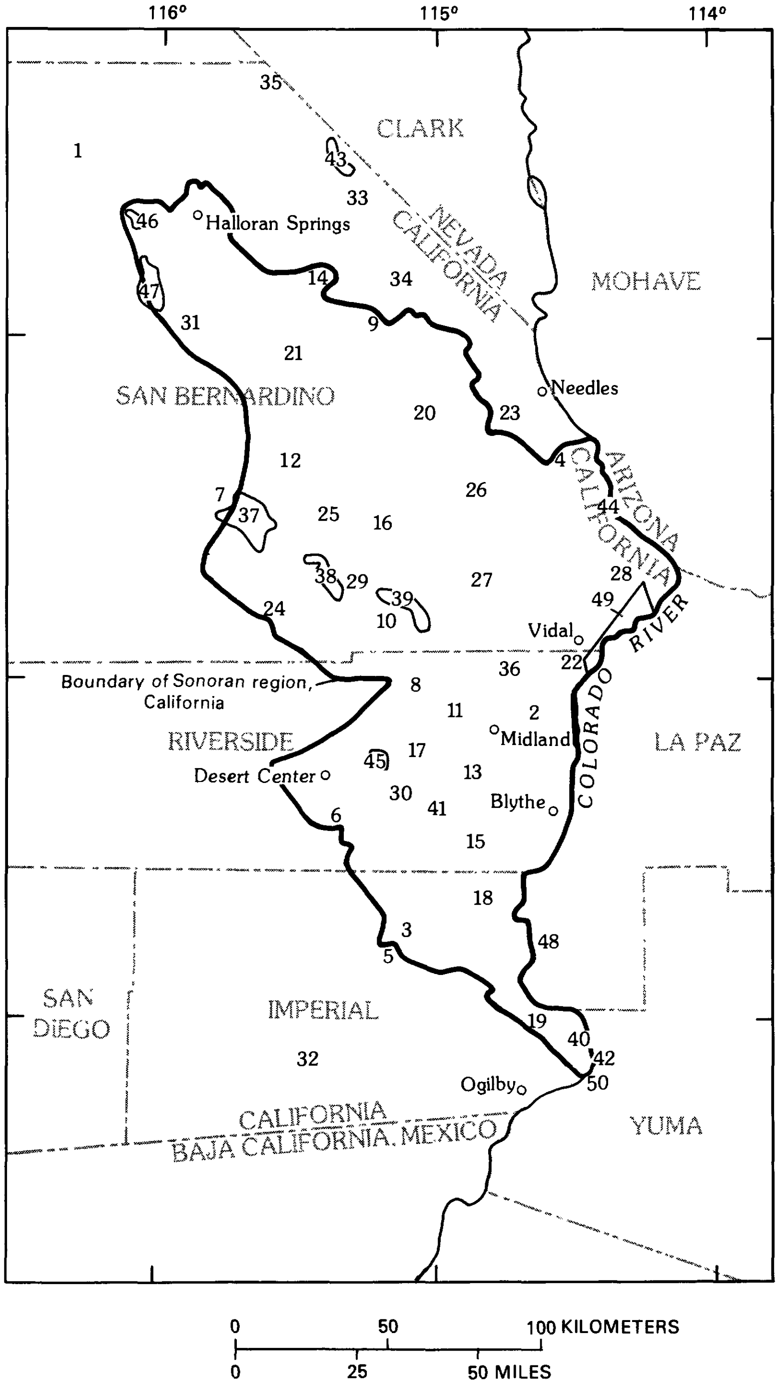
This chapter provides the geologic and hydrologic framework necessary to evaluate the region for relative potential for isolation of high-level radioactive waste. Because of the limited and specific goals of the project, emphasis is placed on the characteristics of the region that relate to waste isolation.

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.

GEOGRAPHIC SETTING

The Sonoran region of California, as defined in this report, of the Basin and Range province is the western part of the Sonoran region that lies entirely within California (pl. 1, fig. 1). The eastern part of the Sonoran region, in southwestern Arizona, is discussed in Chapter D of this Professional Paper. The California part of the Sonoran region, which adjoins the Mojave Desert on the west, Death Valley on the north, and Salton trough on the south, locally has geologic characteristics more like those of the adjoining areas than those of the Sonoran region in Arizona. The region is bounded on the east by the Colorado River from Laguna Dam to Lake Havasu. From there it trends northwest along the Sacramento Mountains, Hackberry Mountain, and Mid Hills, to Silver Lake. From Silver Lake its western boundary goes to Soda Lake then to Bristol Lake, then southeastward through the Sheep Hole, Granite, Chuckwalla, and Chocolate Mountains.

Altitudes of the basin floors commonly range from 150 m to as much as 750 m. The altitudes of the crests of the intervening mountain ranges commonly are 900–1,200 m, but in places are greater than 1,500 m.



EXPLANATION

1-- AVAWATZ MOUNTAINS
2-- BIG MARIA MOUNTAINS
3-- BLUE MOUNTAIN
4-- CHEMEHUEVI MOUNTAINS
5-- CHOCOLATE MOUNTAINS
6-- CHUCKWALLA MOUNTAINS
7-- DISH HILL
8-- GRANITE MOUNTAINS
9-- HACKBERRY MOUNTAIN
10-- IRON MOUNTAINS
11-- LITTLE MARIA MOUNTAINS
12-- MARBLE MOUNTAINS
13-- McCOY MOUNTAINS
14-- MID HILLS
15-- MULE MOUNTAINS
16-- OLD WOMAN MOUNTAINS
17-- PALEN MOUNTAINS
18-- PALO VERDE MOUNTAINS
19-- PICACHO PEAK
20-- PIUTE MOUNTAINS
21-- PROVIDENCE MOUNTAINS
22-- RIVERSIDE MOUNTAINS
23-- SACRAMENTO MOUNTAINS
24-- SHEEP HOLE MOUNTAINS
25-- SHIP MOUNTAINS
26-- STEPLADDER MOUNTAINS
27-- TURTLE MOUNTAINS
28-- WHIPPLE MOUNTAINS
29-- CADIZ VALLEY
30-- CHUCKWALLA VALLEY
31-- DEVILS PLAYGROUND
32-- IMPERIAL VALLEY
33-- IVANPAH VALLEY
34-- LANFAIR VALLEY
35-- MESQUITE VALLEY
36-- RICE VALLEY
37-- BRISTOL LAKE
38-- CADIZ LAKE
39-- DANBY LAKE
40-- FERGUSON WASH
41-- FORD DRY LAKE
42-- IMPERIAL RESERVOIR
43-- IVANPAH LAKE
44-- LAKE HAVASU
45-- PALEN LAKE
46-- SILVER LAKE
47-- SODA LAKE
48-- THREE FINGER LAKE
49-- COLORADO RIVER INDIAN RESERVATION
50-- LAGUNA DAM

FIGURE 1.—Major geographic features of the Sonoran region, California, and vicinity.

ACKNOWLEDGMENTS

This report and the other reports in this series were prepared in cooperation with the States of Arizona, California, Idaho, Nevada, New Mexico, Texas, and Utah. Each of these States was represented by members of the Basin and Range Province Working Group. The cooperating agencies in each State and members and alternates of the Province Working Group are listed following the title page. 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. In the ground-water phase of the study the authors gratefully acknowledge the assistance of William F. Hardt and W.R. Moyle of the U.S. Geological Survey. Mr. Moyle's extensive knowledge of the region and familiarity with the ground-water conditions greatly assisted the authors in preparation of this report.

REFERENCES CITED

Bedinger, M.S., Sargent, K.A., and Brady, B.T., 1985, Geologic and hydrologic characterization and evaluation of the Basin and Range province relative to the disposal of high-level radioactive waste—Part III, Geologic and hydrologic evaluation: U.S. Geological Survey Circular 904-C, 27 p.

Bedinger, M.S., Sargent, K.A., and Langer, W.H., 1989, Studies of geology and hydrology in the Basin and Range province, southwestern United States, for isolation of high-level radioactive waste—Evaluation of regions: U.S. Geological Survey Professional Paper 1370-H [in press].

Bedinger, M.S., Sargent, K.A., Langer, W.H., Sherman, F.B., Reed, J.E., and Brady, B.T., 1989, Studies of geology and hydrology in the Basin and Range province, southwestern United States, for isolation of high-level radioactive waste—Characterization and evaluation: U.S. Geological Survey Professional Paper 1370-A [in press].

Bedinger, M.S., Sargent, K.A., and Reed, J.E., 1984, Geologic and hydrologic characterization and evaluation of the Basin and Range province relative to the disposal of high-level radioactive waste—Part I, Introduction and guidelines: U.S. Geological Survey Circular 904-A, 16 p.

Sargent, K.A., and Bedinger, M.S., 1985, Geologic and hydrologic characterization and evaluation of the Basin and Range province relative to the disposal of high-level radioactive waste—Part II, Geologic and hydrologic characterization: U.S. Geological Survey Circular 904-B, 30 p.

GEOLOGY

By George I. Smith and Robert Streitz[1]

Geologic data relevant to a hydrologic evaluation of the area of interest were first compiled by constructing a series of transverse and longitudinal geologic sections and gravity profiles (Smith, 1987). Where most of the mountain ranges and valleys in this area trend north, the transverse sections (*A–A'*, *B–B'*, and *C–C'* on pl. 2) trend east; where those topographic features trend northwest, the transverse section (*D–D'* on pl. 2) trends northeast. These transverse sections were the major source of geologic control for constructing the longitudinal geologic section (*E–E'* on pl. 2) along the nearly outcrop-free axes of the major valleys.

Extensive literature exists on the geology of the Sonoran region, California. Sources of more detailed data generally are indicated in the collection of transverse or longitudinal cross sections (Smith, 1987), though unpublished data from U.S. Geological Survey studies that are in progress have markedly affected some descriptions and interpretations. The earliest comprehensive study of this entire area was the classic hydrologic and geologic reconnaissance by Thompson (1929); data on many wells and springs included in the volume can never be duplicated, and many of his inferences concerning the regional hydrologic setting have been proven correct. A more recent geologic reconnaissance by Bassett and Kupfer (1964) of the northwestern one-half of the region described here summarizes the state of geologic knowledge of the region at that time. Moyle (1974) compiled a geohydrologic map of the region that reflected the state of hydrologic knowledge at that time. More recent geologic summaries are provided by Burchfiel and Davis (1981) and by the numerous papers contained in volumes edited by Fife and Brown (1980), Howard and others (1981), and Frost and Martin (1982); these publications, and the references cited in them, have been the prime sources of data used in preparing this summary, and they also represent sources of additional information for the interested reader. The most recent geologic compilation of the entire area, as discussed here, is that of Jennings (1977); the fault-tectonic framework of the same area is summarized in the compilation by Jennings (1975). More detailed compilations (1:250,000) of the geology of virtually the entire area discussed here are available from the Kingman (Jennings, 1961), Needles (Bishop, 1963), and Salton Sea (Jennings, 1967) sheets published by the California Division of Mines and Geology in the Geologic Map of California series; a compilation of the gravity data for the region is available at 1:250,000 for the same sheets of the Bouguer Gravity Map of California series (Healey, 1973; Chapman and Rietman, 1978; Biehler and Rotstein, 1979, respectively) published by the same agency.

STRATIGRAPHY

The rocks exposed in the Sonoran region, California, have been divided into units on a combined basis of their ages, lithologies, and our qualitative inferences concerning their probable hydrologic properties. This grouping combines some rock and sediment units that would be subdivided in studies concerned primarily with stratigraphy or geologic history, and separates others that ordinarily would have been combined on the basis of their ages or genesis. This is especially true of the crystalline rock types. Because no predictable differences exist in the hydrologic properties of plutonic, metamorphic, and well-indurated clastic rocks, many of the geologically important details of these rock types are not presented in this summary. The following discussion, therefore, greatly abbreviates what has been published concerning these units. A more geologically orthodox and intermediate-level summary can be found in the Stratigraphic Nomenclature summaries that accompany the Kingman, Needles, and Salton Sea sheets of the Geologic Map of California series, and detailed descriptions of many units are presented by the papers cited here.

PRECAMBRIAN METAMORPHIC ROCKS

A considerable variety of crystalline rocks of known or inferred Precambrian age crop out in the Sonoran region, California. Gneiss, augen gneiss, schist, quartzite, and marble make up large parts of some mountain ranges, especially in the southern part of the region, but metaplutonic rocks are the most abundant rocks in the region as a whole. The metaplutonic rocks range in composition from granite to diorite, and many are characterized by schistose structure and gneissic banding. Pegmatites are rare, and dike swarms of apparent Precambrian age are present in some areas. Radiometric ages indicate two periods of Precambrian intrusion, about 1,700 and 1,400 m.y. (Burchfiel and Davis, 1981, p. 221). As more rocks are dated, and as detailed mapping in these areas is continued, however, many of the so-called Precambrian metaplutonic rocks, including

[1]California Department of Conservation, Division of Mines and Geology.

many with well-developed fabric, are being classified as Mesozoic in age.

Where these rocks are unfractured, their hydrologic properties probably are similar to those of the younger granitic bodies, although, in many instances, the older rocks have undergone extensive deformation. Some of that deformation appears to have been of Precambrian age, and recrystallization may have restored the hydrologic properties of the rocks to those of undeformed materials. The validity of this theory needs to be carefully tested by coring, however, because rocks of this unit probably underlie a large part of the Sonoran region, California, and also the area west of this region where they were not remelted during the Mesozoic episode of batholithic emplacement.

PRECAMBRIAN AND LOWER AND MIDDLE CAMBRIAN SEDIMENTARY ROCKS

Several of the formations included in this group of rocks crop out within the boundaries of the three northern ground-water units, SC–04, SC–05, and SC–06 (fig. 2). They represent a shelfward extension and thinning of the very thick section of miogeosynclinal rocks that underlie much of the Death Valley area. Virtually the entire sequence is composed of siliceous clastic-shelf facies. In the northernmost part of the Sonoran region, California, these clastic facies, or their lateral equivalents, are assigned (in ascending order) to the Johnnie Formation, Stirling Quartzite, Wood Canyon Formation, Zabriskie Quartzite, and Carrara Formation. Cambrian fossils occur first in the Wood Canyon Formation. At the latitude of the Marble Mountains (fig. 1), the older two units have pinched out, and only about 150 m of the Wood Canyon Formation, Zabriskie Quartzite, and Carrara Formation equivalent remain and rest on Precambrian gneiss (Stewart, 1970). Southeast of this area, the Precambrian sedimentary rocks are missing, and this part of the Paleozoic section becomes thinner, metamorphosed, and more easily related to the Tapeats Sandstone and Bright Angel Shale, rocks of the same age that crop out in the Grand Canyon area to the northeast (Hamilton, 1982, p. 4–6; Stone and others, 1983, p. 1136–1144).

The hydrologic properties of these formations are likely to be those of purely clastic, well-indurated rocks. Some carbonate beds are present in almost all the included formations, but they are thin and separated from each other by clastic units.

MIDDLE CAMBRIAN THROUGH MIDDLE PALEOZOIC SEDIMENTARY ROCKS

Three carbonate sedimentary sequences that dominated to the middle of the Paleozoic are described here. They rest conformably on the clastic sequences described above and, like those sequences, represent shelfward extensions of the miogeosynclinal stratigraphic sequences of the Death Valley area. In the Sonoran region, as exemplified by the section in the Providence Mountains, one carbonate-dominant sequence includes the Bonanza King Formation, Nopah Formation, and Sultan Limestone that total about 500 m in thickness. To the west, Ordovician rocks of quite different facies are present but metamorphosed (Carr and others, 1981, p. 17). To the south and east, rocks of Ordovician age appear to be missing and, although the lithologies of the remaining units are similar, they are much thinner and more metamorphosed. Carbonate rock units in these areas are correlated with the Cambrian Muav Limestone, an unnamed Cambrian or Devonian dolomite, and the Devonian Temple Butte Limestone (Stone and others, 1983, fig. 2).

The carbonate-dominant part of this Paleozoic section in the Death Valley area has relatively large values of hydraulic conductivity. However, there is no evidence to indicate similar hydraulic conductivity in the Sonoran region, California. Furthermore, in the Sonoran region, rocks of this group tend to be more intensely deformed and metamorphosed, and they are isolated in relatively small areas surrounded by crystalline rocks, making the hydrologic properties of these rocks of only local significance.

UPPER PALEOZOIC SEDIMENTARY ROCKS

Upper Paleozoic rocks crop out locally in the Sonoran region, California. In the Providence Mountains (fig. 1), which divide ground-water units SC–05 and SC–06, the upper Paleozoic rocks are assigned to the Monte Cristo Limestone and Bird Spring Formation of Carboniferous and Lower Permian ages, units composed of fossiliferous limestone, sandy limestone, and dolomite (Hazzard, 1954, table 1). South and east of that mountain range, however, scattered remnants of correlative clastic and carbonate rocks have been metamorphosed and tectonically thinned. They are most directly correlated with the Grand Canyon sequence: Redwall Limestone, Supai Group, Hermit Shale, Coconino Sandstone, Toroweap Formation, and Kaibab Limestone (Stone and others, 1983, p. 1142–1144, fig. 2).

Carbonate facies dominate these rock units, and they may serve as zones favorable to the transmittal of ground water. As noted previously, however, Paleozoic rock sequences in the Sonoran region, California, are mostly isolated and surrounded by crystalline rocks, making their hydrologic properties of only local significance.

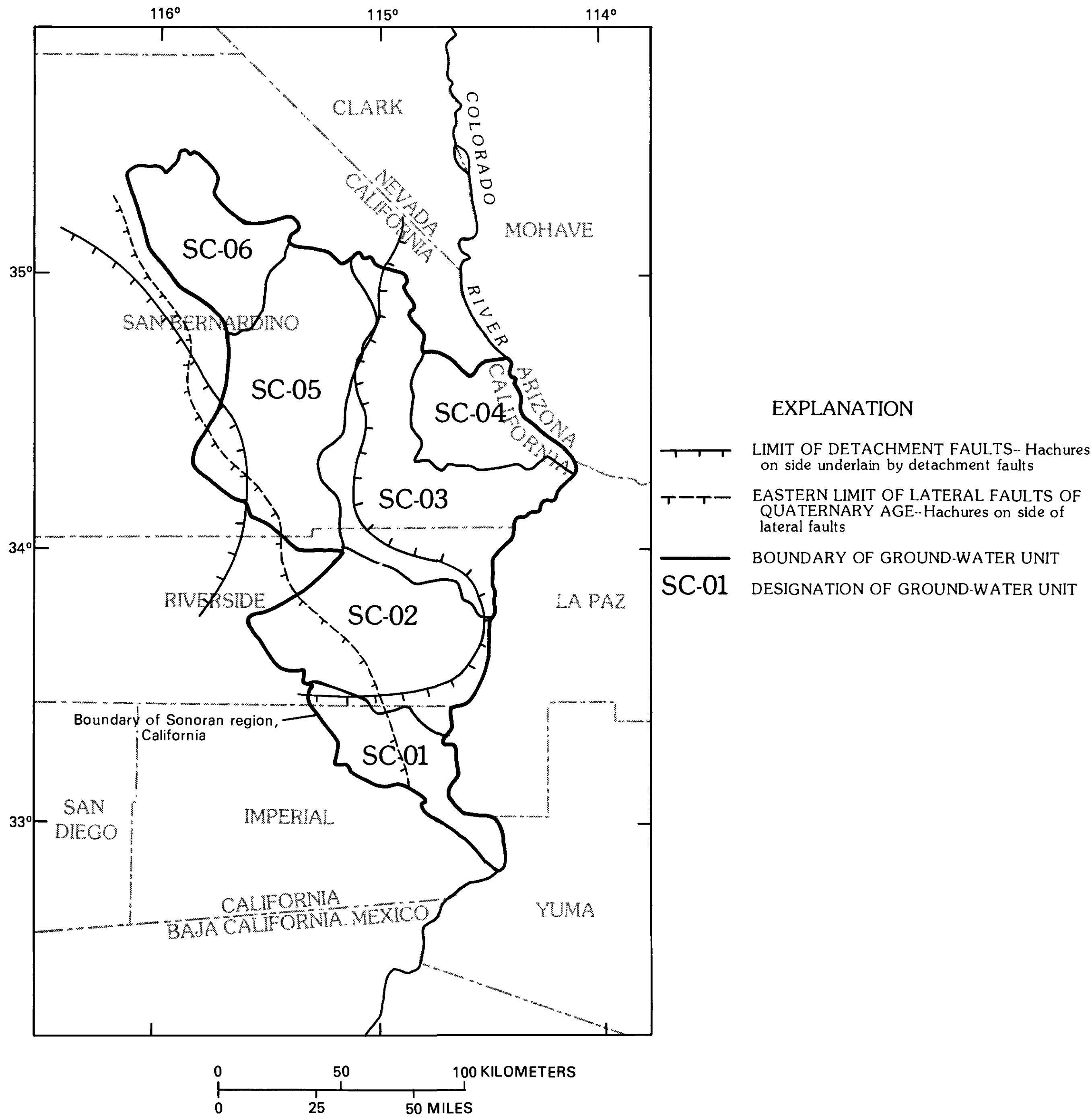


FIGURE 2.—Possible limits of areas underlain by detachment faults and eastern limit of Quaternary lateral faulting in the Sonoran region and vicinity, and ground-water units within the region.

LOWER MESOZOIC METASEDIMENTARY AND METAVOLCANIC ROCKS

About 500 m of lower Mesozoic argillite and limestone, overlain by 2,000 m of metavolcanic rock and interbedded sandstone, crop out along the northern border of ground-water unit SC-06 (Grose, 1959, p. 1523-1529). More coarsely clastic lower Mesozoic rocks, overlain by metavolcanic rocks, are present within ground-water units SC-02 and SC-03. Flows, flow breccias, and welded tuffs composed of dacitic and andesitic materials constitute most of the outcrops of metavolcanic rocks, though volcaniclastic sandstone and quartzite locally are abundant. Some of the volcanic rocks were welded tuffs prior to intense metamorphism (Hamilton, 1982, p. 10–11). More than 7,000 m of siliciclastic rocks overlie the metavolcanic rocks in the central part of ground-water units SC–02 and SC–03 (Pelka, 1973; Harding, 1982), but the siliciclastic rock units are much thinner and more metamorphosed to the east.

Most outcrops of the lower Mesozoic units indicate moderate to severe structural deformation and metamorphism, and their hydrologic properties probably are more a function of those geologic elements than their lithologies. In the Palen and McCoy Mountains, rocks of this group consist of a greenschist facies; in the Big Maria Mountains, they consist of a gneissic facies.

UPPER MESOZOIC PLUTONIC ROCKS

Coarse-grained plutonic rocks, mostly of late Mesozoic age, possibly account for more outcrop area than any other bedrock type exposed in the Sonoran region, California. In the northern and western parts of the region, they almost certainly also underlie much of the Cenozoic basin fill. Radiometric ages on these units generally indicate either a Jurassic or Cretaceous age. Though a latest Permian age has been reported from similar rocks west of the study area, a Triassic age has been reported from such rocks cropping out along the western edge of ground-water units SC–01 and SC–02, and a Tertiary age was reported for plutonic bodies just north and south of the study area (John, 1981, p. 48–49).

Jurassic rocks in the northern one-half of the region are of two types. In ground-water unit SC–06 and the northern part of unit SC–05, plutonic rocks tend to be hornblende- and biotite-bearing monzonite and syenite and have ages between 145 and 158 m.y. To the south, they tend to be minimal-quartz monzogranite and granodiorite and have ages near 165 m.y. The Cretaceous rocks are mostly hornblende-biotite granodiorite and granite that have ages of about 90 m.y., followed by hornblende-biotite granodiorite and two-mica garnet-bearing granite with ages ranging from 82 to 54 m.y. The Cadiz Valley batholith, an example of the last group of Cretaceous plutonic rocks, is composed of three intrusive phases that vary from biotite-sphene granodiorite to garnet-muscovite aplite with estimated intrusion ages ranging from 85 to 75 m.y. (John, 1981, p. 48–50). Southeast of an arc defined approximately by the Old Woman, Granite, and Big Maria Mountains, Jurassic and Cretaceous plutonic rocks generally have been affected by shearing and regional metamorphism; maximum shearing and metamorphism has occurred in ground-water units SC–01 and SC–02 (Hamilton, 1982, p. 11–14).

OLIGOCENE AND MIOCENE SEDIMENTS

Paleocene and Eocene rocks are generally absent in the Sonoran region, California. Upper Oligocene or Miocene deposits in the region mostly were deposited in deep basins that generally had shapes, trends, or distributions that were unrelated to those of present basins. Several thousand meters of coarse redbeds, slide breccias, coarse fluvial gravel, and playa-lake deposits of Oligocene and Miocene age crop out in, and on the flanks of, most of the mountain ranges in the Sonoran region, California (D.M. Miller, U.S. Geological Survey, written commun., 1984; Hamilton, 1982, p. 20), and thick sections probably underlie many of the present valley floors. Their ages, where known, were derived from radiometric determinations on interbedded volcanic rocks or fossils.

The largest volume of sediments was deposited under subaerial conditions, and except for the predominant tuffaceous character of many sections, presently forming alluvial fans provide a modern analog of the processes involved in their deposition (although some of the extremely coarse conglomerate has few modern analogs). Slide breccia and coarse conglomerate characterize the deposits that were near the head of an alluvial fan when the unit was formed, and these generally grade laterally into pebbly sandstone toward the former depocenter of the basin. Some units are characterized by beds of well-sorted coarse sand, and these may represent fluvial environments. Where the Tertiary drainages terminated in closed basins, playa or salt lakes developed in the depocenters, and fine sand, silt, clay, and salt accumulated. Where the Tertiary drainages flowed to the sea, the salts and most of the sediments finer than sand were exported from the area. Deposits of these ages generally are faulted, moderately indurated, and commonly associated with moderate to great volumes of volcanic flows, ash, and pyroclastics.

The hydraulic conductivity of the continental Oligocene and Miocene sedimentary rocks generally is small because cements and chemical precipitates fill the pore spaces.

OLIGOCENE AND MIOCENE VOLCANIC ROCKS

Large masses of Oligocene and Miocene volcanic rocks crop out in some parts of the Sonoran region. Most appear to represent local centers of volcanism although remnants of welded tuff record very large eruptions that blanketed thousands of square kilometers. Rock compositions range from rhyolite to basalt, and their textures indicate deposition as air-fall and welded tuffs, lahars, rubble breccias, flow breccias, and massive flows. Intrusive necks and domes also are widespread. Many of the stratified volcanic rocks are interbedded with tan and red sedimentary rocks.

In ground-water units SC–01 and SC–02, three separable groups of volcanic rocks have been identified (Crowe and others, 1979). The earliest rock, characteristically 26–35 m.y. old, is composed of basaltic to rhyodacitic flows and breccias. The overlying layers, 22–28 m.y. old, include welded ash-flow tuff, rhyodacitic and rhyolitic lava flows, and volcaniclastic rocks. The "capping" volcanic sequence consists of two subunits dated at either 25–29 or 13–22 m.y. with composition varying from olivine basalt to pyroxene dacite. Rocks of all three sequences are calc-alkalic in character.

Volcanic rocks in the mountain ranges bordering and west of ground-water units SC–05 and SC–06 include the same variety of compositions and lithologies described in the paragraph above. They are also calc-alkalic in nature and have ages ranging from older than 23 to about 18 m.y. (Moseley and others, 1982, fig. 3). Similar rocks are exposed in the center of ground-water unit SC–05 where perlite also is present (Miller and others, 1982, p. 96). The welded tuff found near the top of several of these sequences is about 18 m.y. old and is tentatively correlated with the Peach Springs Tuff of Young (1966), first described in Arizona.

PLIOCENE AND LOWER QUATERNARY SEDIMENTS

Most of the rocks and sediments of this group are subaerially deposited sand and gravel that are similar in origin and lithology to those of Miocene and Oligocene age except the younger rocks tend to be less indurated and generally were deposited in nonmarine basins whose shapes and locations are more similar to those of the modern basins.

The sediments of the Bouse Formation are different, however, and may represent an exception to the generalization that Cenozoic sediments and rocks in the Sonoran region, California, were deposited in nonmarine basins. Metzger and others (1973, p. G13–G19, tables 13 and 14) describe the Bouse Formation as a marine to brackish-water sequence. Outcrops generally consist of a basal limestone or marl that commonly overlies tufa deposits that coat the underlying bedrock. The limestone and marl, in turn, are overlain by several meters of nearly horizontal interbedded clay, silt, and sand which contain brackish-water marine-type fossils. In the subsurface, where the unit may be as thick as 275 m, it is composed chiefly of sand, silt, clay, and marl. Fine-grained deposits at depths of 81 and 232 m beneath the surfaces of Cadiz and Danby Lakes, in ground-water units SC–03 and SC–05, also contain brackish-water marine-type fossils, possibly indicating a former extension of the same water body into those depressions (Bassett and others, 1959, p. 106–108). Radiometric dates on a volcanic ash layer in the Bouse Formation range from about 3 to 8 m.y.; its age, therefore, could be considered late Miocene and Pliocene. Although the limited marine or brackish-water fauna in all these deposits indicates a marinelike depositional environment, the small number of fauna indicates that the depositional environment was a marginal one for marine forms. The tufa deposits indicate deposition of the Bouse Formation in an inland brackish lake as being a reasonable alternative hypothesis. After deposition of the Bouse Formation, three episodes of erosion, separated by two periods of fluvial deposition, produced the succession of fluvial deposits and terraces seen today along the Colorado River (Johnson and Miller, 1980, p. 443–446).

Except in areas along the Colorado River and in Ivanpah Valley, few subsurface data exist on the properties of the coarser sediment facies of deposits; water wells deep enough to penetrate these sediments are rare, and logs prepared during drilling commonly are inadequate. Subsurface data from some of the playa- and salt-lake facies are available (Muessig and others, 1957; Bassett and others, 1959; Simoni, 1980a, b), but most cores do not extend to depths of more than about 300 m, where the sediments probably are not more than 1–2 m.y. old. A log from a core hole more than 500 m deep, near the western boundary of ground-water unit SC–06, indicates a great thickness of Miocene or Pliocene mudstone, tuff, and evaporites (Madsen, 1970). We suspect, however, that in the depocenters of bedrock basins, as indicated by present topography or geophysical data, similar deposits of lacustrine silt and clay and salt extend downward nearly to crystalline basement.

UPPER QUATERNARY SEDIMENTS AND ALLUVIUM

All sediments of these ages are of continental origin. Fine to coarse gravel, deposited by intermittent streams flowing down the flanks of both closed and open basins, cover at least one-half of the Sonoran region, California. The enormous variation in the capacity of flowing water to transport debris in this region of infrequent, but large, thunderstorms result in a very large variation in erosion rates and, consequently, in the sizes of fragments that constitute these deposits. The storm variability apparently becomes more extreme toward the southern and eastern parts of the region, and the upper Quaternary deposits correspondingly become more coarse and poorly sorted in those directions. Whereas Holocene alluvium is nearly free of secondary carbonate, upper and middle Pleistocene soils, probably representing the last million years, contain quantities of carbonate somewhat proportionate to their age (Shlemon, 1980, p. 394–398). This secondary carbonate tends to decrease the permeability of the alluvium and restrict infiltration of precipitation.

Where the present drainage terminates within the basin, playa lakes have formed because of the modern arid climate. The presence (or absence) of salts in playa lakes may provide a major indication of the hydrologic discontinuity (or continuity) of the subsurface fill with adjacent, lower basins. Where the major source of salt is surface water, salt will accumulate as relatively clean and continuous layers if the volume of water is small enough that overflow does not take place yet large enough to form a perennial lake, and if relatively small quantities of clay and silt flow into the lake. Where the volume of water is small in relation to its clastic content, lacustrine "salty" clay and silt will be deposited. Where the chief source of accumulating salt is encroaching ground water, salt crystallizes as a result of capillary transport of the water to a depth near the land surface where it evaporates. Playa sediments can be salt-free if the water level is below the depth of evaporation from the water table and the basin has a subsurface hydrologic connection with another area at lower altitude, allowing the salts to be transported from the basin in solution, or if the volume of surface-inflowing water during wet periods caused overflow which transported accumulated salts to other basins or to the sea. Examples of these depositional environments are discussed in the section on Geomorphology.

UPPER QUATERNARY VOLCANIC ROCKS

Several volcanic fields and flows, traditionally considered to be of late Quaternary age, are within the region. Their erupted products, virtually all of which are alkali olivine basalts, lie at or very near the present land surface, even though their conduits extended to great depths as indicated by an abundance of mantle-derived xenoliths composed of peridotites and pyroxenites. Age estimates based on the fresh-appearing lava surfaces and scarcely eroded cones have dated the eruptions as late Quaternary. A much larger range of ages, however, recently has been documented. Dish Hill, near the western edge of ground-water unit SC–05, has been dated by fission-track and K–Ar methods as being about 2 m.y. old (Boettcher, 1982). The youngest Amboy Crater flow, which is nearby, is covered by Holocene lake deposits (Miller and others, 1982, p. 96). The youngest flow of the so-called Quaternary Cima volcanic field, near the center of ground-water unit SC–06, has been dated by ^{14}C and glass-hydration methods as being about 400 yr old (Dokka and Glazner, 1982, p. 23), although Dohrenwend and others (1984, p. 165) suggested, on the basis of several criteria, an early Holocene age for this flow. Dohrenwend and others (1984) determined the oldest flows in this field to be 7.6 m.y. old, or as old as Miocene age.

STRUCTURE

Evidence of structural deformation as old as Precambrian and Paleozoic is present in and near the Sonoran region of California. Much of it is fragmentary, however, and depends principally on projection from the north where the record of events during those times is more complete. Summaries of the evidence for, and syntheses of, these structural events are provided by Burchfiel and Davis (1975, p. 364–373; 1981, p. 236–237).

Mesozoic and Cenozoic structural deformation, however, was more important than the earlier events in determining the present distribution of rocks in the region. Details of the evidence for structural events of this age, in many of the individual ranges in the Sonoran region, California, are presented in the volume edited by Frost and Martin (1982). As summarized by Burchfiel and Davis (1981, p. 236–246, figs. 9–6 and 9–8), the earliest deformation in this sequence may have been of latest Permian age, but most of it was younger. Early Mesozoic deformation mostly consisted of eastward-directed thrusting accompanied by major deformation of the upper Precambrian, Paleozoic, and lower Mesozoic sedimentary rocks, but some Precambrian and lower Mesozoic crystalline rocks also were involved. The depth at which the exposed thrusting took place appears to have increased toward the southeastern part of the region; the "style" of thrusting became more ductile in that direction, and migmatization and very intense metamorphism are observed in the more extreme examples (Hamilton, 1982, p. 13–17). Many of the later Mesozoic plutonic rocks postdate the thrusting in their areas, but in several ranges in the east-central part of region, other plutonic rocks as young as latest Cretaceous age are mylonitized.

Folds and faults of Cenozoic age are widespread in the region. Little is known of the very early Cenozoic tectonic history because of the apparent absence of rocks of that age in the region. About 25 m.y. ago, however, a brief period of intense crustal extension accompanied by volcanic eruptions, clastic sedimentation, faulting, and tilting appears to have affected much of the Sonoran region, California. East-northeast-trending antiforms and synforms also appear to have been created at the same time by some poorly understood mechanism. Near the western edges of ground-water units SC–05 and SC–06, this extensional episode started about 23 m.y. ago and ended 20 m.y. ago (Dokka and Glazner, 1982, p. 37); in the eastern parts of ground-water units SC–02, SC–03, and SC–04, comparable volcanic and tectonic events lasted from about 26–17 m.y. ago (Hamilton, 1982, p. 21). Relatively undeformed strata are only slightly younger than the youngest tilted strata and are superposed on them. Extension appears generally to have been in the northeast direction. It took place along deep, subhorizontal detachment faults that now separate the underlying core complex from the overlying crustal rocks that slumped passively, along downward-flattening faults, into the new space created by the crustal extension. The high-angle normal and strike-slip faulting that accompanied and followed extensional faulting, apparently serving as uncoupling surfaces between areas undergoing different degrees of extension, is found throughout much of the region (Hamilton, 1982, p. 21; Dokka and Glazner, 1982, p. 35–36).

The structural concept of detachment faulting is relatively new, however, and it has not been tested uniformly across the entire region. The geologic sections (Smith, 1985; pl. 2, this chapter) only show detachment faults near recently mapped areas where they have been documented. Work currently in progress, however, indicates to many that detachment faults underlie mountain ranges and valleys throughout large areas. The terrane possibly underlain by such structures is shown in figure 2.

Younger faults are mostly northwest trending, strike slip, and of apparent Quaternary age. They formed in response to stresses that are most likely related to those responsible for the San Andreas fault, which is southwest of the study area (Garfunkel, 1974; Cummings, 1976, 1981). Many of these faults, especially those west of ground-water units SC–05 and SC–06, have been active in late Cenozoic—even historic—time, and they constitute part of the reason those areas were excluded from this study. Some of these faults extend into the western parts of ground-water units SC–01, SC–02, and SC–05 (fig. 2). Less recently active, northwest-trending, and possibly right-lateral faults extend southeastward along a zone from about the Sheephole Mountains, through ground-water units SC–05 and SC–02. A conjugate set of left-lateral faults occurs in the western part of ground-water unit SC–02, and they strike eastward into, and appear truncated by, the northwest-trending faults (Hope, 1969; Powell, 1982).

The Garlock fault, a major left-lateral fault with abundant evidence of late Quaternary displacements, which is northwest of the study area and whose eastern segment lies along the northern edge of the Avawatz Mountains (fig. 1), joins the Death Valley fault zone, also northwest of the study area, and appears to continue to the southeast under alluvium. West of ground-water unit SC–06, faults subparallel to, and west of, that continuation are shown as being active in Quaternary time on the Fault Map of California (Jennings, 1975). Davis (1977) eliminated the possibilities, however, for a significant southeastward continuation of the Death Valley–Garlock fault zone itself, and he concluded that it dies out east of the Avawatz Mountains and north of hydrologic unit SC–06. Jennings' (1975) map also shows a few short fault traces that were active in Quaternary time in ground-water units SC–01 and SC–02, but it shows no Quaternary faults in the remaining parts of the study area—in spite of the proximity of the historically active San Andreas and related faults in the Imperial Valley immediately southwest of the study area. The tectonic quiescence east of this zone has been attributed to the zone's superposition over a ridge or hinge on the Moho discontinuity which is designated the Mohave-Sonoran tectonic boundary (Fuis, 1981, p. 36, fig. 3c). Two grabens that disrupt Quaternary alluvial surfaces near the Colorado River may represent exceptions to this general quiescence, but a nontectonic origin for them is quite possible (Purcell and Miller, 1980).

Present rates of folding and tilting are difficult to establish geologically. In a tectonically active area near the Garlock fault, Smith and Church (1980) reported maximum rates of altitude change along resurveyed benchmark lines of 0.1–0.2 (mm/km)/yr, but this would only produce a change of slope of 0.6°–1.2° in 100,000 yr. Within the study area, tectonic deformation appears to be much slower, and probably can be ignored except near active faults.

The hydrologic characteristics of rocks within the study area undoubtedly are affected by both the areal and depth distribution of major faults. For example, seismic data indicate that the depth of fractures in crystalline rocks of the southwestern Mojave Desert varies from about 500 m in relatively unfaulted areas to 2,500 m in areas closer to the San Andreas fault (Fuis, 1981, fig. 2). The fault zones themselves, however, may be either hydrologic conduits (if open fractures are present) or barriers (if gouge fills the fault zone). The extent and depths of detachment faults may be important in determining deep ground-water flow patterns and rates. As seen on outcrops, detachment faults are characterized by thick zones of relatively impervious gouge and mylonite, but the adjoining rocks are normally extensively fractured and porous. However, fractures tend to close with depth, thereby decreasing the hydraulic conductivity (Bedinger and others, 1989). Furthermore, in the Sonoran region, flow anomalies that would be obvious as large springs discharging from permeable fault zones are not present.

GEOMORPHOLOGY

All except two ground-water units, SC–01 and SC–04, in the Sonoran region, California, include one or more topographically closed basins and contain one or more dry lakes. The basins containing Bristol, Cadiz, and Danby Lakes, in ground-water units SC-05 and SC-03, appear to be examples of basins that are accumulating salt introduced by ground-water influx; the saline beds in all three have the impure and discontinuous qualities described in an earlier section as products of this mechanism, and virtually no evidence exists of former standing bodies of water (Ver Plank, 1958, fig. 5; Bassett and others, 1959, p. 110-111). These dry lakes are areas of ground-water discharge (Langer and others, 1984) under the present interpluvial climate regimes.

The hydrologic conditions at Soda Lake and Silver Lake in ground-water unit SC-06 were described by Thompson (1929) on the basis of observations in 1917 and 1919. The playa of Soda Lake has a puffy, salt-encrusted, dry-mud surface but no salt beds were encountered at depth in core holes (Muessig and others, 1957). The surficial saline deposits were described by Thompson (1929) as being more abundant on the western side of the lake. This description agrees with the ground-water discharge area at the lake identified by W.R. Moyle, Jr. (U.S. Geological Survey, written commun., 1983), shown in Langer and others (1984). In contrast, Thompson (1929) noted that at Silver Lake "***alkali is entirely absent". Silver Lake is a few meters lower topographically than Soda Lake from which it is naturally separated by a low divide; the divide has been breached by man-made channels as observed by Thompson (1929). During historic times Silver Lake has been the terminus of the Mojave River basin, and at infrequent intervals waters of the Mojave River inundate the lake. Thompson (1929) believed the difference in the surfaces of Soda and Silver Lakes to be caused by differences in the depths to ground water. Evapotranspiration of ground water is occurring at Soda Lake because the ground water is at shallow depth, but it is not occurring at Silver Lake because ground water there lies below the depth of evaporation from the surface. The water table apparently continues to slope to the north beneath the topographic divide between Silver Lake and the Amargosa River basin, providing subsurface drainage into the Death Valley area.

Palen Lake and Ford Dry Lake in ground-water unit SC-02, however, have no bedded salt beneath their surfaces (Simoni, 1980a, b). The lack of salt probably is because ground-water discharge from the unit is to the Colorado River (Moyle, 1974; Langer and others, 1984) and the depth to ground water at these lakes is too great to support evaporation from the surface.

Topographic configurations and landforms in the desert environment have relatively long durations. Even though the erosion rates are very rapid during intense rainfall, as noted in the description of Quaternary sediments, those events occur infrequently. Also, rocks and sediments not in the path of established channels largely escape the greatest erosion. Most of the playa lakes cored as parts of the investigations cited above are underlain by at least 150-300 m of lake deposits showing that the closed-basin configuration has existed for an appreciable length of geologic time, possibly 1-2 m.y. For example, 693 m of lacustrine sediment in Searles Valley, about 110 km northwest of Silver Lake, represents 3.2 m.y. of closed-basin deposition (Smith and others, 1983).

Volcanic rocks are especially resistant to destruction by geologic processes. The Dish Hill volcanic crater, described in the section on upper Quaternary volcanic rocks, retains its crater shape even though it is 2 m.y. old. In the Cima volcanic field, Dohrenwend and others (1984, p. 166) noted that 5 m of constructional relief has been preserved on flow surfaces as old as 0.15 m.y., but that such relief is decreased to less than 10 percent of that height on flows 0.7 m.y. or older, though cone and flow morphology is recognizable in much older rocks.

Smaller and more easily eroded features also survive for long periods. Upper Cenozoic subaerial deposits in ground-water unit SC-03 were described (Carr and Dickey, 1980; Dickey and others, 1980) as "Old alluvium" of "Pleistocene and Pliocene" age, on the combined bases of the sediment lithologies, preserved-surface character, and soil development. These authors cited several Th-U dates on the postdepositional soil carbonate, some of which exceed the methods limit of about 300,000 yr, showing that some alluvial deposits have retained their original surfaces and resisted destruction for a large part of the last million years.

Observations like these tend to substantiate that erosion of the desert landforms—from the scale of basin configurations to smaller landforms and relatively easily eroded surfaces—is a geologically slow process. Erosional processes likely need to operate for several million years to change the fundamental geomorphic character of the desert landscape.

REFERENCES CITED

Bassett, A.M., and Kupfer, D.H., 1964, A geologic reconnaissance in the southeastern Mojave Desert: California Division of Mines and Geology Special Report 83, 43 p.

Bassett, A.M., Kupfer, D.H., and Barstow, F.C., 1959, Core logs from Bristol, Cadiz, and Danby, Dry Lakes, San Bernardino County, California: U.S. Geological Survey Bulletin 1045-D, p. 97-138.

Bedinger, M.S., Langer, W.H., and Reed, J.E., 1989, Hydraulic properties of rocks, *in* Bedinger, M.S., Sargent, K.A., Langer, W.H., Sherman, F.B., Reed, J.E., and Brady, B.T., Studies of geology and hydrology in the Basin and Range province, southwestern United States, for isolation of high-level radioactive waste—Basis of characterization and evaluation: U.S. Geological Survey Professional Paper 1370-A [in press].

Biehler, Shaw, and Rotstein, Yair, 1979, Bouguer gravity map of California, Olaf P. Jenkins edition, Salton Sea sheet: California Division of Mines and Geology, scale 1:250,000.

Bishop, C.C., 1963, Geologic map of California, Olaf P. Jenkins edition, Needles sheet: California Division of Mines and Geology, scale 1:250,000.

Boettcher, A.J., 1982, Dish Hill, *in* Cooper, J.D., compiler, Guidebook of geologic excursions in the California desert, Field Trip number 2, Late Cenozoic tectonic and magmatic evolution of the central Mojave Desert, California, R.F. Dokka and A.F. Glazner, leaders: Geological Society of America 78th Annual Meeting of the Cordilleran Section, Anaheim, Calif., April 19-21, 1982, p. 89.

Burchfiel, B.C., and Davis, G.A., 1975, Nature and controls of Cordilleran orogenesis, Western United States—Extensions of an earlier synthesis: American Journal of Science, v. 275-A, p. 363-396.

Burchfiel, B.C., and Davis, G.A., 1981, Mojave Desert and environs, Chapter 9, *in* Ernst, W.G., ed., The geotectonic development of California—Rubey volume 1: Englewood Cliffs, N.J., Prentice-Hall, p. 217-251.

Carlisle, Donald, Kettler, R.M., and Swanson, S.C., 1980, Uranium- and thorium-bearing facies of the late Proterozoic Kingston Peak Formation, Death Valley region, California, *in* Fife, D.L., and Brown, A.R., eds., Geology and mineral wealth of the California Desert, Dibblee volume: Santa Ana, Calif., South Coast Geological Society Field Trip, October 11-12, 1980, p. 379-386.

Carr, M.D., Poole, F.G., Harris, A.G., and Christiansen, R.L., 1981, Western facies Paleozoic rocks in the Mojave Desert, California, *in* Howard, K.A., Carr, M.D., and Miller, D.M., eds., Tectonic framework of the Mojave and Sonoran Deserts, California and Arizona: U.S. Geological Survey Open-File Report 81-503, p. 15-17.

Carr, W.J., and Dickey, D.D., 1980, Geologic map of the Vidal, California, and Parker SW, California-Arizona Quadrangles: U.S. Geological Survey Miscellaneous Investigations Series Map I-1125, scale 1:24,000.

Chapman, R.H., and Rietman, J.D., 1978, Bouguer gravity map of California, Olaf P. Jenkins edition, Needles sheet: California Division of Mines and Geology, scale 1:250,000.

Crowe, B.M., Crowell, J.C., and Krummenacher, Daniel, 1979, Regional stratigraphy, K-Ar ages, and tectonic implications of Cenozoic volcanic rocks, southeastern California: American Journal of Science, v. 279, no. 2, p. 186-216.

Cummings, David, 1976, Theory of plasticity applied to faulting, Mojave Desert, southern California: Geological Society of America Bulletin, v. 87, no. 5, p. 720-724.

Cummings, David, 1981, Mechanics of fault deformation and seismotectonic zoning, Mojave Desert area, California, *in* Howard, K.A., Carr, M.D., and Miller, D.M., eds., Tectonic framework of the Mojave and Sonoran Deserts, California and Arizona: U.S. Geological Survey Open-File Report 81-503, p. 21-22.

Davis, G.A., 1977, Limitations on displacement and southeastward extent of the Death Valley fault zone, California, *in* Hays, W.W., ed., Ground shaking hazard, an important consideration in land-use planning—Short contributions to California geology: California Division of Mines and Geology Special Report 129, p. 27-33.

Dickey, D.D., Carr, W.J., and Bull, W.B., 1980, Geologic map of the Parker NW, Parker, and parts of the Whipple Mountains SW and Whipple Wash Quadrangles, California and Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-1124, scale 1:24,000.

Dohrenwend, J.S., McFadden, L.D., Turrin, B.D., and Wells, S.G., 1984, K-Ar dating of the Cima volcanic field, eastern Mojave Desert, California—Late Cenozoic volcanic history and landscape evolution: Geology, v. 12, no. 3, p. 163-167.

Dokka, R.K., and Glazner, A.F., 1982, Field trip roadlog—Late Cenozoic tectonic and structural evolution of the central Mojave Desert, California, *in* Cooper, J.D., compiler, Guidebook of geologic excursions in the California desert, Field Trip number 2, Late Cenozoic tectonic and magmatic evolution of the central Mojave Desert, California, R.F. Dokka and A.F. Glazner, leaders: Geological Society of America, 78th Annual Meeting of the Cordilleran Section, Anaheim, Calif., April 19-21, 1982, p. 1-30.

Fife, D.L., and Brown, A.R., 1980, eds., Geology and mineral wealth of the California Desert, Dibblee volume: Santa Ana, Calif., South Coast Geological Society Field Trip, October 11-12, 1980, 575 p.

Frost, E.G., and Martin, D.L., eds., 1982, Mezozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada—Anderson-Hamilton volume: San Diego, Calif., Cordilleran Publishers, 608 p.

Fuis, G.S., 1981, Crustal structure of the Mojave Desert, California, *in* Howard, K.A., Carr, M.D., and Miller, D.M., eds., Tectonic framework of the Mojave and Sonoran Deserts, California and Arizona: U.S. Geological Survey Open-File Report 81-503, p. 36-38.

Garfunkel, Zvi, 1974, Model for the late Cenozoic tectonic history of the Mojave Desert, California, and for its relation to adjacent areas: Geological Society of America Bulletin, v. 85, no. 12, p. 1931-1944.

Grose, T.L.T., 1959, Structure and petrology of the northeast part of the Soda Mountains, San Bernardino County, California: Geological Society of America Bulletin, v. 70, no. 12, p. 1509-1547.

Hamilton, Warren, 1982, Structural evolution of the Big Maria Mountains, northeastern Riverside County, southeastern California, *in* Frost, E.G., and Martin, D.L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada—Anderson-Hamilton volume: San Diego, Calif., Cordilleran Publishers, p. 1-27.

Harding, L.H., 1982, A progress report on the tectonic significance of the McCoy Mountains Formation, southeastern California and southwestern Arizona, *in* Frost, E.G., and Martin, D.L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River Region, California, Arizona, and Nevada—Anderson-Hamilton volume: San Diego, Calif., Cordilleran Publishers, p. 135.

Haxel, Gordon, and Dillon, John, 1978, The Pelona-Orocopia Schist and Vincent-Chocolate Mountain thrust system, southern California, *in* Howell, D.G., and McDougall, K.A., eds., Mesozoic paleogeography Symposium 2: Society of Paleontologists and Mineralogists, Pacific Section, p. 453-469.

Hazzard, J.C., 1954, Rocks and structure of the northern Providence Mountains, San Bernardino County, California, *in* Jahns, R.H., ed., Geology of southern California, Chapter 4, Structural features: California Division of Mines Bulletin 170, p. 2, scale 1:31,680, p. 27-35.

Healey, D.L., 1973, Bouguer gravity map of California, Olaf P. Jenkins edition, Kingman sheet: California Division of Mines and Geology, scale 1:250,000.

Hewett, D.F., 1956, Geology and mineral resources of the Ivanpah Quadrangle, California and Nevada: U.S. Geological Survey Professional Paper 275, 172 p.

Hope, R.A., 1969, The Blue Cut fault, southeastern California: U.S. Geological Survey Professional Paper 650-D, p. D116-D121.

Howard, K.A., Carr, M.S., and Miller, D.M., 1981, Tectonic framework of the Mojave and Sonoran Deserts, California and Arizona: U.S. Geological Survey Open-File Report 81-503, 125 p.

Howard, K.A., Stone, Paul, Pernokas, M.A., and Marvin, R.F., 1982, Geologic and geochronologic reconnaissance of the Turtle Mountains area, California—West border of the Whipple Mountains detachment terrane, *in* Frost, E.G., and Martin, D.L., eds, Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: San Diego, California, Cordilleran Publishers, p. 341-349.

Jennings, C.W., 1961, Geological map of California, Olaf P. Jenkins edition, Kingman sheet: California Division of Mines and Geology, scale 1:25,000.

______1967, Geologic map of California, Olaf P. Jenkins edition, Salton Sea sheet: California Division of Mines and Geology, scale 1:250,000.

______1975, Fault map of California with locations of volcanoes, thermal springs, and thermal wells: California Division of Mines and Geology Geologic Data Map Series, Map 1, scale 1:750,000.

______1977, Geologic map of California: California Division of Mines and Geology Geologic Data Map Series, Map 2, scale 1:750,000.

John, B.E., 1981, Reconnaissance study of Mesozoic plutonic rocks in the Mojave Desert region, *in* Howard, K.A., Carr, M.D., and Miller, D.M., eds., Tectonic framework of the Mojave and Sonoran Deserts, California and Arizona: U.S. Geological Survey Open-File Report 81-503, p. 48-50.

Johnson, Carl, and Miller, D.G., 1980, Late Cenozoic alluvial history of the lower Colorado River, *in* Fife, D.L., and Brown, A.R., eds., Geology and mineral wealth of the California Desert, Dibblee volume: Santa Ana, Calif., South Coast Geological Society Field Trip, October 11-12, 1980, p. 441-446.

Langer, W.H., Moyle, W.R., Jr., Woolfenden, Linda, and Mulvihill, D.A., 1984, Maps showing ground-water levels, springs, and depth to ground water, Basin and Range province, southern California: U.S. Geological Survey Water-Resources Investigations Report 83-4116-B, scale 1:500,000, 6 p.

Loeltz, O.J., Irelan, Burdge, Robison, J.H., and Olmsted, F.H., 1975, Geohydrologic reconnaissance of the Imperial Valley, California: U.S. Geological Survey Professional Paper 486-K, p. K1-K54.

Madsen, B.M., 1970, Core logs of three test holes in Cenozoic lake deposits near Hector, California: U.S. Geological Survey Bulletin 1296, 43 p.

Metzger, D.G., Loeltz, O.J., and Irelan, Burdge, 1973, Geohydrology of the Parker-Blythe-Cibola area, Arizona and California: U.S. Geological Survey Professional Paper 486-G, p. G1-G130.

Miller, D.M., Howard, K.A., and John, B.E., 1982, Preliminary geology of the Bristol Lake region, Mojave Desert, California, *in* Cooper, J.E., ed., Guidebook of geologic excursions in the California desert, Field Trip number 2, Lake Cenozoic tectonic and magmatic evolution of the central Mojave Desert, California, R.F., Dokka and A.F. Glazner, leaders: Geological Society of America 78th Annual Meeting of the Cordilleran Section, Anaheim, Calif., April 19-21, 1982, p. 91-100.

Moseley, C.G., Williamson, D.A., and Miller, S.T., 1982, The stratigraphy of the northeastern Cady Mountains and its implications for the Cenozoic volcanic evolution of the Mojave Desert, *in* Ingersall, R.V., and Woodburne, M.O., eds., Cenozoic nonmarine deposits of California and Arizona: Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, Calif., April 16, 1982, p. 75-82.

Moyle, W.R., Jr., 1974, Geohydrologic map of southern California: U.S. Geological Survey Water-Resources Investigations Open-File Report 48-73, scale 1:500,000.

Muessig, Siegfried, White, G.M., and Byers, F.M., Jr., 1957, Core logs from Soda Lake, San Bernardino County, California: U.S. Geological Survey Bulletin 1045-C, p. 81-96.

Pelka, G.J., 1973, Geology of the McCoy and Palen Mountains, southeastern California: Santa Barbara, Calif., University of California, Ph. D. dissertation, 162 p.

Powell, R.E., 1982, Crystalline basement terranes in the southern eastern Transverse Ranges, California, *in* Cooper, J.D., ed., Guidebook of geologic excursions in the Transverse Ranges: Geological Society of America, 70th Annual Meeting of the Cordilleran Section, Anaheim, Calif., April 12-21, 1982, p. 109-136.

Purcell, C.R., and Miller, D.G., 1980, Grabens along the lower Colorado River, California and Arizona, *in* Fife, D.L., and Brown, A.R., eds., Geology and mineral wealth of the California Desert, Dibblee volume: Santa Ana, Calif., South Coast Geological Society Field Trip, October 11-12, 1980, p. 475-484.

Shlemon, R.J., 1980, Quaternary soil—Geomorphic relationships, southeastern Mojave Desert, California and Arizona, *in* Fife, D.L., and Brown, A.R., eds., Geology and mineral wealth of the California Desert, Dibblee volume: Santa Ana, Calif., South Coast Geological Society Field Trip, October 11-12, 1980, p. 388-402.

Simoni, T.R., Jr., 1980a, Geophysical, lithologic, and water quality data from test wells on Ford Dry Lake, Riverside County, California: U.S. Geological Survey Open-File Report 80-1277, 1 sheet.

Simoni, T.R., Jr., 1980b, Geophysical and lithologic data from test well on Palen Dry Lake, Riverside County, California: U.S. Geological Survey Open-File Report 80-014, 1 sheet.

Simpson, R.W., Bracken, R.E., and Stierman, D.J., 1985, Aeromagnetic, Bouguer gravity, and interpretation maps of the Sheep Hole-Cadiz Wilderness Study Area, San Bernardino County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1615-B, scale 1:62,500, 4 sheets.

Smith, G.I., 1987, Transverse and longitudinal geologic cross sections of southeast California: California Division of Mines and Geology Open-File Report [in press].

Smith, G.I., Barczak, V.J., Moulton, G.F., and Liddlcoat, J.C., 1983, Core KM-3, a surface-to-bedrock record of late Cenozoic sedimentation in Searles Valley, California: U.S. Geological Survey Professional Paper 1256, 24 p.

Smith, G.I., and Church, J.P., 1980, Twentieth-century crustal deformation in the Garlock fault-Slate Range area, southeastern California: Geological Society of America Bulletin, v. 91, p. 1, p. 524-534.

Stewart, J.H., 1970, Upper Precambrian and lower Cambrian strata in the south-western Great Basin, California and Nevada: U.S. Geological Survey Professional Paper 620, 206 p.

Stone, Paul, Howard, K.A., and Hamilton, Warren, 1983, Correlation of metamorphosed Paleozoic strata of the southeastern Mojave Desert region, California and Arizona: Geological Society of America Bulletin, v. 94, no. 10, p. 1135-1147.

Thompson, D.G., 1929, The Mojave Desert region, California: U.S. Geological Survey Water-Supply Paper 578, 759 p.

Ver Planck, W.E., 1958, Salt in California: California Division of Mines Department of Natural Resources Bulletin 175, 168 p.

Young, R.A., 1966, Cenozoic geology along the edge of the Colorado Plateau in northwestern Arizona: Dissertation Abstracts, v. 27, no. 6, sec. B, p. 1994.

POTENTIAL HOST MEDIA FOR RADIOACTIVE WASTE

By K.A. Sargent

Potential host media for a high-level radioactive waste repository in the Sonoran region, California, include intrusive rocks, such as granite and other coarse-grained plutonic rocks; ash-flow tuff, especially where densely welded and having a thickness greater than 100 m; and basalt and basaltic andesite lava flows where greater than 100 m thick. Other, less abundant rock types such as shallow rhyolite intrusions and volcanic mudflow breccias occur in the region and may have potential as host rocks.

Argillaceous sedimentary and metasedimentary rocks, where present, are less than 150 m thick and generally structurally complex, and, therefore, appear to have no potential as host media. Johnson (1984) summarized their occurrence and thickness in southern California. Salt and other evaporitic deposits appear to have no potential as host media in this region.

In addition, the above-mentioned potentional host media and possibly other rock types and basin-fill deposits have potential as host media in the unsaturated zone. The outcrop areas of potential host rock and areas believed to be underlain by thick unsaturated zones in the Sonoran region, California, are shown in plate 3.

INTRUSIVE ROCKS

Granitic rocks are widely distributed, occurring in large outcrop areas throughout the region. In groundwater unit SC–01 southwest of Blue Mountain, granite and quartz monzonite are of Tertiary and Mesozoic age and may postdate major structural deformation. In ground-water unit SC–02, granite, quartz monzonite, and granodiorite are, in part, of Cretaceous and Jurassic age. They commonly are fractured and sheared, especially in the eastern part of ground-water unit SC–02. An outcrop area of about 8 km^2 at the western end of the Little Maria Mountains is Tertiary granite that is tectonically undeformed and unfoliated. Other granitic rocks in the Little Maria Mountains are of Cretaceous age, and are fractured and sheared. Granite in the Big Maria Mountains is extensively fractured and sheared. In the Chuckwalla Mountains in the southwestern part of ground-unit SC–02, Cretaceous and especially Precambrian granites are extensively sheared. In the Mule Mountains in the the southern part of groundwater unit SC–02, diorite, quartz diorite, and granite, of Precambrian age, also are extensively sheared and foliated.

In ground-water unit SC–03, granitic rocks in the Turtle Mountains are of Jurassic and Cretaceous age, are part of a metamorphic core complex and are extensively sheared. The Riverside Mountains consist of granodiorite and monzogranite of Cretaceous and Jurassic age.

The Needles metamorphic core complex in the northern Sacramento Mountains in the northern part of ground-water unit SC–03 contains Precambrian foliated granitic and dioritic gneiss. Along the boundary between ground-water units SC–03 and SC–04, granitic sill-like bodies are mostly mylonitized and possibly may be horizontal slices between detachment faults.

In the Iron Mountains along the boundary between ground-water units SC–03 and SC–05, granitic rocks of Cretaceous age intrude older granite masses, which are very strongly mylonitized. In the Old Woman and Piute Mountains along the boundary between units SC–03 and SC–05, Cretaceous plutonic granitic rocks that are undeformed and unmetamorphosed cut thrust faults in older Precambrian gneiss. Stepladder pluton, a granodiorite, crops out in the Stepladder Mountains along the boundary between ground-water units SC–03 and SC–04; no structural descriptions are available. In the Chemehuevi Mountains in the northern part of groundwater unit SC–04, Cretaceous granitic rocks that are part of a metamorphic core complex are cut by detachment faults and are locally mylonitized.

The ranges in the southern part of ground-water unit SC–05, south of Bristol and Cadiz Lakes, contain mostly mylonitized Cretaceous and Jurassic granitic rocks. Ship Mountains in ground-water unit SC–05 consist of granitic rocks of Jurassic age; no structural descriptions are available. In the Marble Mountains in ground-water unit SC–05, Jurassic granite intrudes foliated Precambrian granitic rocks. In the Providence Mountains along the boundary between units SC–05 and SC–06, the Mesozoic granite present there has not been described structurally. In the Mid Hills along the boundary between ground-water units SC–05 and SC–06 and in the northern part of unit SC–06, the drainage divide is formed by the Teutonia Quartz Monzonite of Cretaceous age, which generally displays only minor shearing and mylonitization.

Other granitic stocks and plugs occur in the Sonoran region of California that are not mentioned here. Available information on them was summarized by Hills and Lopez (1984).

TUFFACEOUS ROCKS

Ash-flow tuffs occur in ground-water units SC-01 and SC-02 in the Sonoran region of California. One unit, the ignimbrite along Ferguson Wash, is widespread and becomes as thick as 350 m in the southeastern part of ground-water unit SC-01 near Picacho Peak. This flow thins northward to Three Finger Lake. Ash flows on the border between ground-water units SC-01 and SC-02 in the Palo Verde Mountains are very thin, probably less than 50 m. The tuffs have been dated at 22-28 m.y., contemporaneous with basin-and-range faulting. Tuff units were summarized by Jenness and Lopez (1984).

BASALTIC ROCKS

Basaltic rocks occur as widely scattered small outcrops in each ground-water unit of the region. Basalts are locally as thick as 125 m but generally are less than 20 m thick. They have been dated as mostly 14-17 m.y. old. Most are vesicular olivine basalt, commonly interbedded with clastic volcanic rocks. Available information on basaltic rocks in the Sonoran region of California was summarized by Roggensack and Lopez (1984).

EVAPORITE DEPOSITS

Exploratory holes drilled as deep as 326 m into Soda Lake (Muessig and others, 1957) and into Bristol, Cadiz, and Danby Lakes (Bassett and others, 1959) penetrated no evaporite beds of suitable thickness. Only at Bristol and Cadiz Lakes was bedded salt penetrated. At Bristol lake the recovered core of a 307-m-deep hole contained 40 percent halite in scattered crystals and massive halite beds as much as about 2.5 m thick. At Cadiz Lake, a drill hole penetrated one salt layer about 0.3 m thick, 2.75 m below the surface.

UNSATURATED ZONE

The distribution of the unsaturated zone where it is 150 m or more thick was conservatively mapped by Langer and others (1984) and may be considerably more extensive than shown. Unsaturated sections of greater than 150 m in thickness are widespread beneath most of the higher mountain ranges. Many of the sheared granite and metamorphic rocks are in areas of thick unsaturated sections. Tuff and basalt generally are above the water table but are of insufficient (or unknown) thickness to serve as potential host rocks in the unsaturated zone.

REFERENCES CITED

Bassett, A.M., Kupfer, D.H., and Barstow, F.C., 1959, Core logs from Bristol, Cadiz, and Danby Dry Lakes, San Bernardino County, California: U.S. Geological Survey Bulletin 1045-D, p. 97-138.

Hills, F.A., compiler, 1984, Maps showing outcrops of granitic and silicic shallow intrusive rocks, Basin and Range province, southern California: U.S. Geological Survey Water-Resources Investigations Report 83-4116-D, scale 1:500,000, 1 sheet, 38 p.

Jenness, J.E., and Lopez, D.A., compilers, 1984, Maps showing outcrops of pre-Quaternary ash-flow tuffs, Basin and Range province, southern California: U.S. Geological Survey Water-Resources Investigations Report, 83-4116-F, scale 1:500,000, 1 sheet, 7 p.

Johnson, W.D., Jr., compiler, 1984, Maps showing outcrops of thick, dominantly argillaceous sedimentary and metasedimentary rocks, Basin and Range province, southern California: U.S. Geological Survey Water-Resources Investigations Report 83-4116-E, scale 1:500,000, 1 sheet, 6 p.

Langer, W.H., Moyle, W.R., Woolfenden, L.R., and Mulvihill, D.A., 1984, Maps showing ground-water levels, springs, and depth to ground water, Basin and Range province, southern California: U.S. Geological Survey Water-Resources Investigations Report 83-4116-B, scale 1:500,000, 2 sheets, 6 p.

Muessig, Siegfried, White, G.N., and Byers, F.M., Jr., 1957, Core logs from Soda Lake, San Bernardino County, California: U.S. Geological Survey Bulletin 1045-C, p. 81-96.

Roggensack, Kurt, and Lopez, D.A., compilers, 1984, Map showing outcrops of basaltic rocks of early Quaternary and Tertiary age, Basin and Range Province, southern California: U.S. Geological Survey Water-Resources Investigations Report 83-4116-G, scale 1:500,000, 1 sheet, 13 p.

QUATERNARY TECTONISM

By K.A. SARGENT and GEORGE I. SMITH

Quaternary tectonic conditions of the Sonoran region of California are characterized by seismicity, heat flow, Quaternary faulting, late Cenozoic volcanic activity, and vertical crustal movement of the region. Features associated with each of these conditions are depicted in figure 3.

SEISMICITY

Nine earthquakes are listed in a compilation for the Sonoran region, California, by Algermissen and others (1983). Except for an overlapping pair of epicenters with Richter (surface wave) magnitudes 5–6 and 6–7 (fig. 3), just north of Imperial Reservoir, the earthquakes had magnitudes less than 4. The two large earthquakes are responsible for the strain release of 10 as shown on the strain-release map of Algermissen and others (1983) and in figure 3. Epicenters west of the region are responsible for a strain release of 10 in the western part of the region (fig. 3).

HEAT FLOW

Twenty-four heat-flow measurements were reported in the Sonoran region of California (J.H. Sass, U.S. Geological Survey, written commun., 1982). Five heat-flow values that exceed 2.5 HFU occur on the western side of the region (fig. 3). The maximum heat-flow value is 5.53 HFU. Sass places the entire region in the 1.5–2.5 HFU interval.

QUATERNARY FAULTING

In regional compilations, Nakata and others (1982) and Jennings (1975) showed Quaternary faults as sparsely distributed and mostly confined to the periphery of the region (fig. 3). Nakata and others (1982) have designated one fault segment (eastern side of the region) as Holocene, as young as 10,000 yr, and the others as late Quaternary.

LATE CENOZOIC VOLCANIC ROCKS

The Cima volcanic field occurs in the northern part of the region east of Soda Lake (fig. 3). Here flows of hawaiite, alkali olivine basalt, and basinite are late Miocene to Holocene in age (Dohrenwend and others, 1984; fig. 4). The youngest flow is 330–480 yr old based on a ^{14}C date on charcoal in the base of the flow (Katz and Boettcher, 1980) and on glass-hydration methods (Dokka and Glazner, 1982, p. 23), although Dohrenwend and others (1984) infer this flow to be no younger than early Holocene. Chesterman (1982) reports small remnants of a probable Pleistocene basalt flow northeast of Ogilby in Imperial County. Other small outcrops of upper Cenozoic volcanic rocks in the region are basaltic and believed to be older than 1 m.y. (Luedke and Smith, 1981).

VERTICAL CRUSTAL MOVEMENT

The southern part of the Sonoran region of California is undergoing uplift at the rate of 4 mm/yr (fig. 3) based on geodetic-leveling data (Gable and Hatton, 1983). The southwestern part of the region is being uplifted at the rate of 4 m to about 10 m per 10,000 yr (0.4–1.0 mm/yr) based on geology, geomorphology, and radiocarbon dates (Gable and Hatton, 1983).

PHOTOLINEATIONS

Studies of linear features in the region north of lat 34° N. by T.W. Offield (U.S. Geological Survey, written commun., 1983), using Landsat multispectral scanner images, indicate a principal northwest trend which parallels and coincides with many of the known older faults as compiled by Jennings (1975).

The linear features seen in Landsat images are alignments of topographic and tonal features. Many features, such as slope breaks are related to faulting and erosion; some are stratigraphically controlled erosional features; still others may be of unknown origin or not related to geologic processes. Major, persistent photolineations need to be investigated if an area is selected for further study.

REFERENCES CITED

Algermissen, S.T., Askew, B.L., Thenhaus, P.C., Perkins, D.M., Hanson, S., and Bender, B.L., 1983, Seismic energy release and hazard estimation in the Basin and Range province: U.S. Geological Survey Open-File Report 83-358, 13 p.

Askew, Bonney, and Algermissen, S.T., 1983, An earthquake catalog for the Basin and Range province, 1803–1977: U.S. Geological Survey Open-File Report 83-86, 21 p.

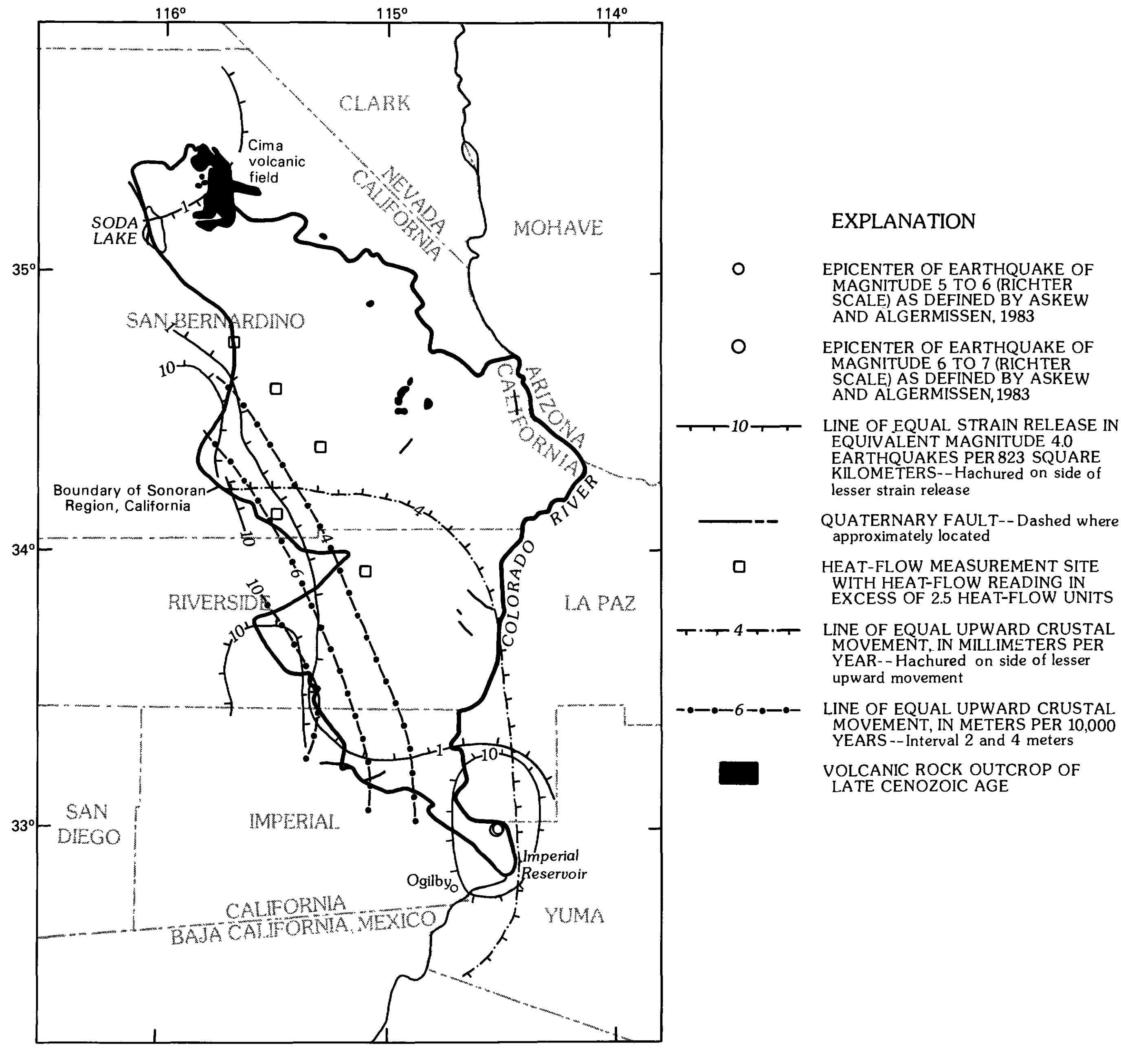


FIGURE 3.—Quaternary tectonic features in the Sonoran region and vicinity.

Chesterman, C.W., 1982, Potentially active volcanic zones in California, *in* Martin, R.C., and Davis, J.F., eds., Status of volcanic prediction and emergency response capabilities in volcanic hazard zones of California: California Division of Mines and Geology Special Publication 63, p. 9-16.

Dohrenwend, J.S., McFadden, L.D., Turrin, B.D., and Wells, S.G.,

FIGURE 4.—View of part of the Cima volcanic field east of Baker, Calif., looking north-northeast toward Clark Mountain. Cinder cones and flows are of late Miocene to Holocene age. Photograph by John S. Shelton, 1967.

1984, K-Ar dating of the Cima volcanic field, eastern Mojave Desert, California—Lake Cenozoic volcanic history and landscape evolution: Geology, v. 12, no. 3, p. 163-167.

Dokka, K.F., and Glazner, A.F., 1982, Field trip roadlog—Late Cenozoic tectonic and structural evolution of the central Mojave Desert, California, *in* Cooper, J.D., compiler, Guidebook of geologic excursions in the California desert, Field Trip number 2, Lake Cenozoic tectonic and magmatic evolution of the central Mojave Desert, California, K.F. Dokka and A.F. Glazner, leaders: Geological Society of America 78th Annual Meeting of the Cordilleran Section, Anaheim, Calif., April 19-21, 1982, p. 1-30.

Gable, D.J., and Hatton, Tom, 1983, Maps of vertical crustal movements in the conterminous United States over the last 10 million years: U.S. Geological Survey Miscellaneous Investigations Series Map I-1315, scale 1:5,000,000, 2 sheets.

Jennings, C.W., 1975, Fault map of California, with locations of volcanoes, thermal springs and thermal wells: California Division of Mines and Geology Geologic Data Map 1, scale 1:750,000.

Katz, Marvin, and Boettcher, Art, 1980, The Cima volcanic field, *in* Fife, D.L., and Brown, A.R., eds., Geology and mineral wealth of the California Desert: Santa Ana, Calif., South Coast Geological Society, Dibblee volume, p. 236-241.

Luedke, R.G., and Smith, R.L., 1981, Map showing distribution, composition, and age of late Cenozoic volcanic centers in California and Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I-1091-C, scale 1:1,000,000.

Nakata, J.D., Wentworth, C.M., and Machette, M.N., 1982, Quaternary fault map of the Basin and Range and Rio Grande rift provinces, Western United States: U.S. Geological Survey Open-File Report 82-579, scale 1:2,500,000, 2 sheets.

GROUND-WATER HYDROLOGY

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

The Sonoran region of California is arid, and annual precipitation varies from less than 80 mm to as great as 250 mm in one mountain range. Free-surface evaporation ranges from 1,750 mm/yr to more than 2,540 mm/yr. Average annual precipitation is less than 80 mm in the basin parts of ground-water units SC–01, SC–02, SC–03, and SC–05. Annual average precipitation is as great as 250 mm in the Turtle Mountains between ground-water units SC–03 and SC–04, and 200 mm in the Mid Hills in the northern part of ground-water unit SC–05. The region includes topographically closed basins (ground-water units SC–05 and SC–06) and basins from which ground water drains to the Colorado River (ground-water units SC–01, SC–02, SC–03, and SC–04).

MAJOR HYDROGEOLOGIC UNITS

Basin fill, including alluvial material of stream valleys, occurs largely in structural basins and is as thick as 1,500 m. The thickest sections commonly underlie Pleistocene lake areas or are adjacent to the Colorado River. Basin fill covers more than 50 percent of the area.

The basin fill consists of nonindurated to indurated sedimentary terrestrial deposits consisting largely of poorly to moderately sorted mixtures or bedded deposits of gravel, sand, silt, and clay derived from the consolidated rocks in the nearby mountains. The fill also contains fine-grained lake deposits, composed of silt and clay, and evaporites. The upper part of the stratigraphic sequence of basin-fill deposits in the Needles area (Metzger and Loeltz, 1973) and in the Lower Colorado River–Imperial Valley area (Olmsted and others, 1973) has been described from driller's logs. These sequences may be similar to those of nearby basins. The typical section consists of about 60 m of coarse sand and gravel overlying as much as 10 m of clay of the Bouse Formation. Deeper basins typically contain thick, fine-grained lake deposits overlying clay of the Bouse Formation.

Volcanic rocks are grouped hydrologically as tuff, basaltic lava flows, and undifferentiated volcanic rocks. Undifferentiated volcanic rocks include flows, ash falls, and pyroclastics of Tertiary and Quaternary age, with some thin, interbedded terrestrial deposits. Undifferentiated volcanic rocks overlie older consolidated rocks and are scattered throughout the region; their maximum thickness is about 600 m.

Tuff of Tertiary age is most prominent near the divide between ground-water units SC-01 and SC-02 where the thickness possibly is as much as 600 m.

Basaltic lava flows of Tertiary age are scattered throughout the region, commonly in association with other, undifferentiated volcanic rocks from which they were subdivided. Individual flows commonly are 15 m thick, and aggregate thicknesses of flows commonly are less than 60 m.

Mixed sedimentary and metasedimentary rocks, including coarse clastic fanglomerate of Tertiary age, and carbonate rocks of Tertiary and Paleozoic age are scattered throughout the region. Coarse clastics of unknown thickness, possibly 100–300 m, include sandstone, conglomerate with some carbonate rocks, shale, and volcanic-rock interbeds. Carbonate rocks, possibly as much as 2,600 m thick, include limestone and dolomite with some metasedimentary rocks (marble, quartzite), clastic sediments, and gypsum.

Crystalline rocks are widespread and underlie the entire region at depth. The rocks in this hydrogeologic unit include metamorphic rocks and felsic and mafic intrusive igneous rocks. Metamorphic rocks include metasediments and metavolcanics of Precambrian to Paleozoic age. Intrusive igneous rocks include felsic to intermediate rocks of Precambrian to Tertiary age.

GROUND-WATER FLOW REGIME

Ground-water recharge must be small because of the small precipitation and the great potential evaporation. Water excess probably occurs as the result of the few infrequent intense thunderstorms that result in floods. Infrequent floods in the Mojave River basin have been studied by Durbin and Hardt (1974), who tabulated 18 floods that reached Barstow, Calif., about 96 river kilometers upstream from the terminus of the Mojave River basin in ground-water unit SC–06. The headwaters of the Mojave River are in the San Bernardino and San Gabriel Mountains, which are 150 km southwest of ground-water unit SC–06 and which receive as much as 1,000 mm of precipitation per year. Busby (1966) showed that the runoff is less than 2.5 mm/yr throughout most of the region with a maximum of 5 mm/yr or slightly more from the mountainous area on the southern border of the region. Estimates of recharge to desert basins in southern California and Nevada have been made by several investigators. Rantz and Eakin (1971) estimated recharge from areas receiving less than 205 mm of precipitation annually to be less than

3 percent of annual precipitation. Sass and Lachenbruch (1982, p. 16–25) have estimated from geothermal data that downward percolation, in the saturated zones at Yucca Mountain at the Nevada Test Site about 170 km northeast of the study area, is 1–10 mm/yr or about 0.7–7 percent of precipitation. Using an empirical method, Rush (1970, p. 15) estimated the recharge rate for Yucca Flat at the Nevada Test Site to be less than 5 mm/yr or less than 3 percent of precipitation. Recharge from precipitation in the Sonoran region, California, probably is less than 3 percent of precipitation, and probably ranges from less than 2 mm/yr in the basins to less than 6 mm/yr in the small mountain ranges that receive 200 mm or more precipitation per year.

Discharge of ground water in the closed basins primarily is to the playa areas where the ground water is near the land surface, and to the Colorado River in the basins tributary to that river. The relatively few small-quantity [a few L/min (liters per minute)] springs that have temperatures near the mean annual ambient air temperature (cold springs) discharge water from consolidated rock. Warm springs mapped by the California Division of Mines and Geology (1980) have spring discharges ranging from 4 to 95 L/min. Withdrawal of ground water from most of the ground-water units is small to negligible. Withdrawal from a part of ground-water unit SC–02 was reported as 11 hm^3 during 1966 (Bedinger, Langer, and Moyle, 1984).

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]

Hydrogeologic unit	Map symbol (pl. 4)	K/ϕ	Hydraulic gradient
Ash-flow tuff	t	1×10^{-1}	0.03
Basin fill	a	6×10^{1}	.003
Carbonate rocks	c	1×10^{1}	.003
Coarse-grained clastic rocks	s	2×10^{-1}	.03
Crystalline rocks:			
Metamorphic rocks	m	2×10^{-1}	.03
Granitic rocks	g	2×10^{-1}	.03
Mafic intrusive rocks	z	2×10^{-1}	.03
Lava flows	b	3×10^{0}	.03
Mixed sedimentary and metasedimentary rocks.	u	2×10^{-1}	.03
Volcanic rock, undifferentiated	v	1×10^{-1}	.03

GROUND-WATER FLOW ANALYSIS

AREAL GROUND-WATER FLOW

Ground-water traveltime near the water table was analyzed using the procedure described in Chapter A (Bedinger, Sargent, and others, 1989). The relative velocities in the hydrogeologic units are shown in plate 4. Relative velocities are reported because site-specific data are not available for the region. The values of hydraulic properties of the units and hydraulic gradients used in estimating relative ground-water velocities are given in table 1.

The hydraulic gradients for the hydrogeologic units are representative gradients obtained from the water-level contour map of the region (Langer and others, 1984). The ratio of hydraulic conductivity to effective porosity was estimated using the values in Chapter A (Bedinger, Langer, and Reed, 1989), 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 in plate 5, as are flow paths along which the relative traveltimes were calculated, and the major discharge areas, which are the Colorado River and playa discharge areas.

The relative traveltimes indicated in the map from divide areas to discharge areas are extremely conservative because actual flow paths in recharge areas dip steeply below the water table; therefore, both flow paths and traveltimes are much longer. The relative traveltimes are useful for comparing relative velocities near the water table and for calculating relative traveltimes at shallow depths between nearby points. A more realistic estimate of relative traveltime between widely spaced points, such as from near a water-table divide to a discharge area, is given in the cross sections.

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 in Chapter A of this report (Reed, 1989). The map location of the sections and the model parameters and results are shown in plate 6. The values of hydraulic properties of the rock units in the sections used in analysis of the ground-water flow are given in table 2.

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

The hydrogeologic sections give a more realistic concept of the traveltime between widely spaced points in

TABLE 2.—*Hydraulic properties of hydrogeologic units used in cross-sectional models*
[K, hydraulic conductivity, in meters per day; ϕ, effective porosity; ---, hydrogeologic unit not present]

Rock type	Symbol	Hydrogeologic sections on plate 6							
		A-A'		*B-B'*		*C-C'*		*D-D'*	
		K	ϕ	K	ϕ	K	ϕ	K	ϕ
Coarse-grained basin fill.	a	1×10^{0}	1.8×10^{-1}	2×10^{0}	1.8×10^{-1}	1×10^{0}	1.8×10^{-1}	2×10^{0}	1.8×10^{-1}
Fine-grained basin fill.	A	2×10^{-4}	3.2×10^{-1}	2×10^{-4}	3.2×10^{-1}	2×10^{-4}	3.2×10^{-1}	2×10^{-4}	3.2×10^{-1}
Coarse-grained clastic rocks.	s	--	--	--	--	3×10^{-2}	1.8×10^{-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}	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}	3×10^{-7}	1×10^{-4}
Carbonate rocks	c	--	--	--	--	3×10^{-3}	1×10^{-2}	--	--
Undifferentiated volcanic rocks.	v	4×10^{-4}	4×10^{-3}	--	--	--	--	--	--

the region, for example, between the water-table divide areas and the discharge areas. As shown in the sections, the flow paths in the upstream parts (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 10^5–10^8. 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 10^3 or greater exist at the water table in all hydrogeologic sections, and areas with relative traveltimes ranging from 10^6 to 10^8 exist within 1,000 m of the water table in all sections.

QUALITY OF GROUND WATER

The quality of ground water in the Sonoran region of California is characterized by the areal distribution of dissolved solids (fig. 5) and predominant chemical constituents in solution (fig. 6). These maps are generalized from those by Thompson and others (1984). The maps of Thompson and others were compiled from the water-quality files of the U.S. Geological Survey (WATSTORE) and published reports. The data are mostly from nongeothermal springs and wells less than 150 m in depth in alluvial and basin-fill deposits. The concentration of dissolved solids is less than 500 mg/L in about two-thirds of the region. Areas of ground water containing more than 500 mg/L of dissolved solids are along the Colorado River in Chuckwalla and Rice Valleys, and near the dry lakes of the region—Danby, Cadiz, Bristol, Soda, and Silver Lakes. The highest dissolved-solids concentrations, a few hundred thousand milligrams per liter, are at Danby, Cadiz, and Bristol Lakes. Most of the ground water of the region is sodium bicarbonate type, occurring over about three-fourths of the region. Calcium magnesium bicarbonate-type, sulfate-type, and chloride-type waters are proportioned within a few percent of each other over the remainder of the region. Calcium magnesium bicarbonate-type waters occur in and near ground-water divide areas and upgradient areas; sulfate-type water occurs in and near natural discharge areas, commonly appearing to be transitional to chloride-type water, which occurs beneath dry lakes, playas, and in a few areas adjacent to the Colorado River.

PLEISTOCENE HYDROLOGIC CONDITIONS

The climate of pluvial epochs during the Pleistocene in the Basin and Range province has been estimated from Pleistocene plant debris and lake levels. Estimates of climatic conditions include a greater water yield resulting either solely from lower temperatures (Galloway, 1970; Brakenridge, 1978) or from both lower temperatures and greater precipitation (Mifflin and Wheat, 1979; Spaulding, 1984). There is evidence that a Pleistocene lake occupied the Soda Lake and Silver Lake basin in the Sonoran region of California. Perennial marshes with the water table at the land surface are believed to have occupied the now-dry playas of Cadiz, Danby, and Bristol Lakes; the ground-water level is currently (1984) near the surface in these dry lakes.

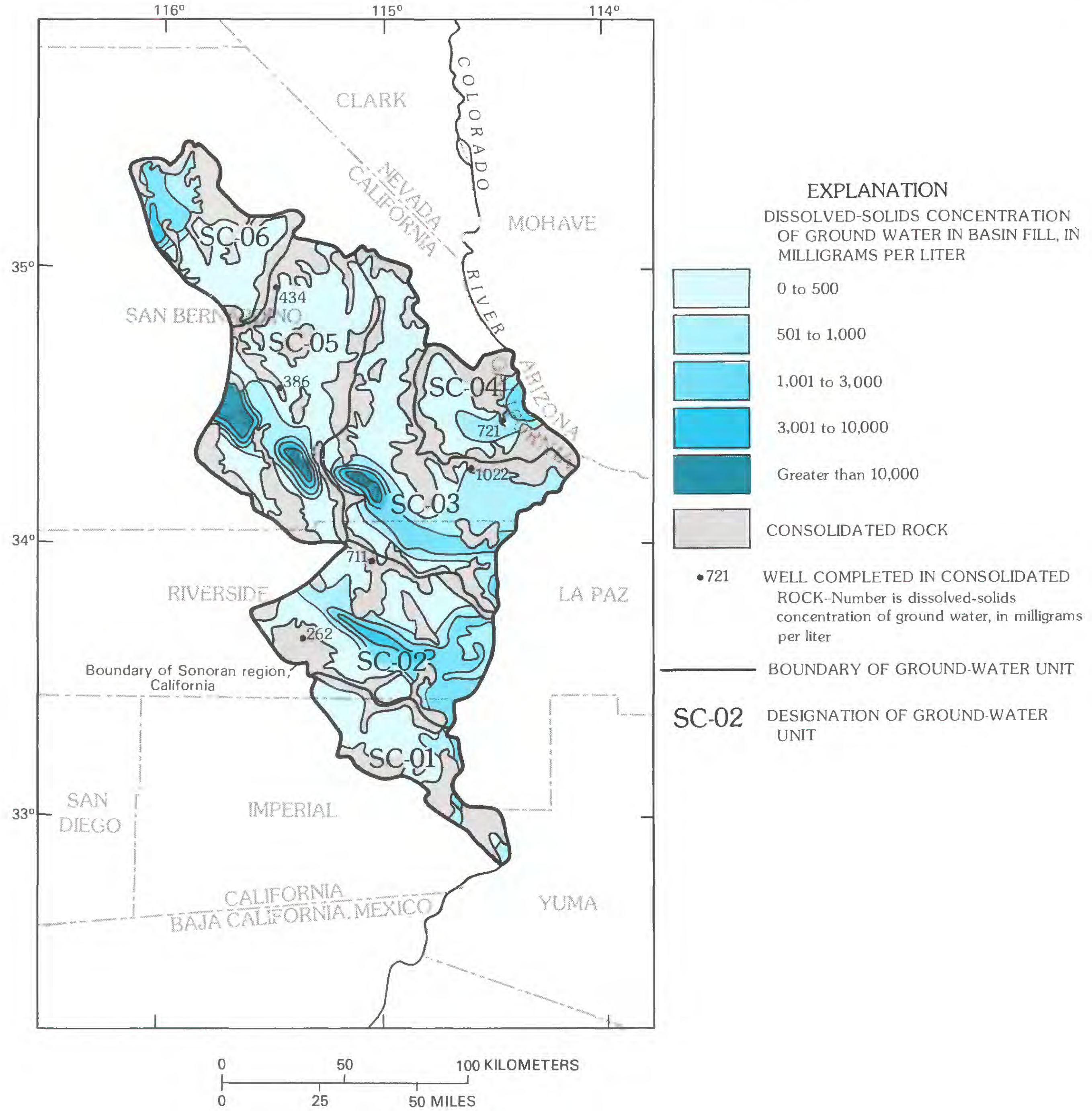


FIGURE 5.—Dissolved-solids concentration of ground water.

During the pluvial times of the Pleistocene there was greater recharge and surface runoff than at the present time. Increased recharge would tend to increase the ground-water gradient toward the discharge areas. The increase in recharge during pluvial times would depend on the increase in precipitation, the seasonal distribution of precipitation, and the demands for moisture by evaporation and by transpiration. If precipitation during a pluvial regime occurred largely during the summer as a result of convective thunderstorms, when the evaporation demand would have been great, the increase in water surplus for recharge would have been less than if the precipitation had occurred in the winter. A relatively small increase in recharge during the last

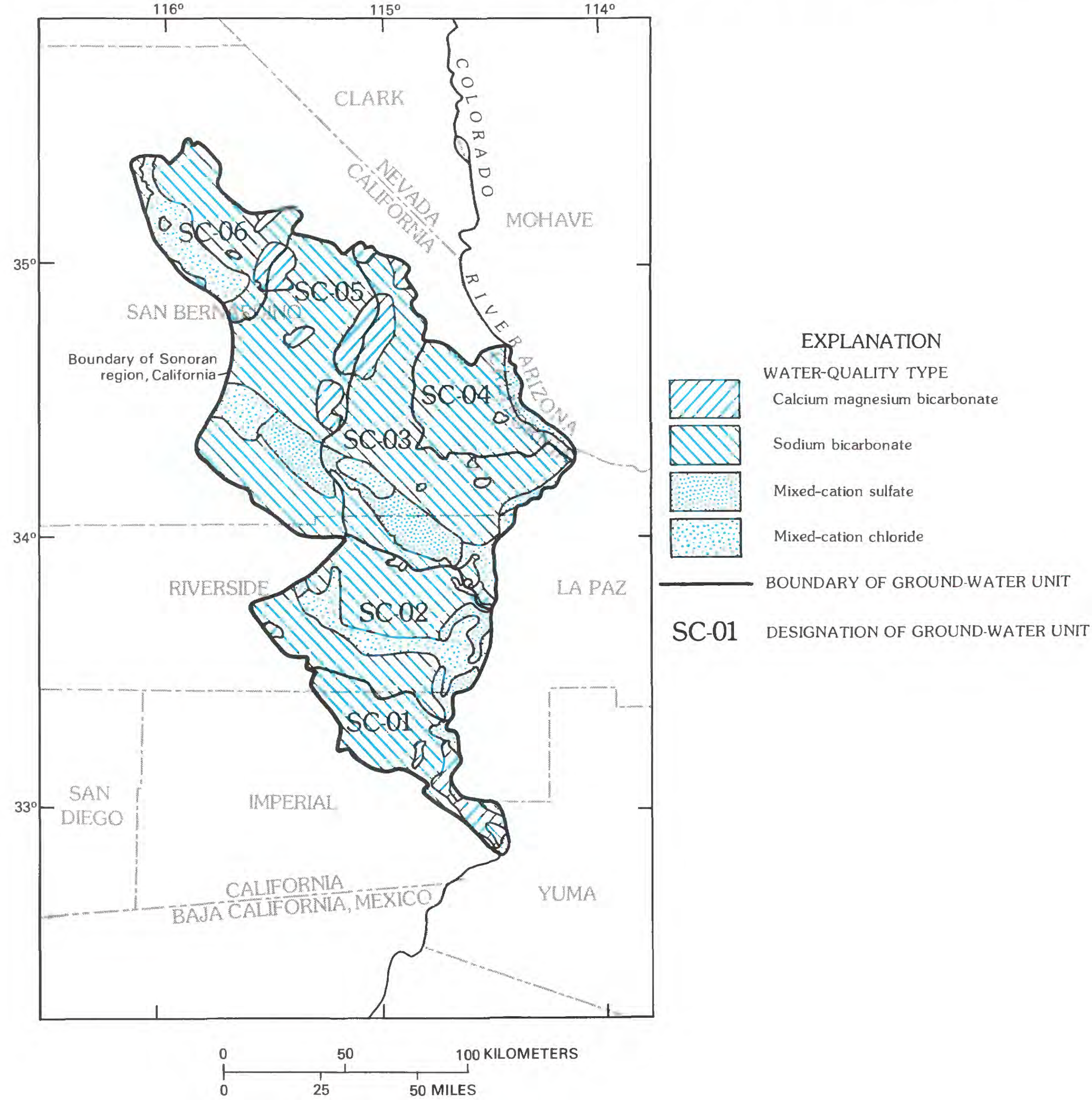


FIGURE 6.—Distribution of chemical types of ground water.

full glacial may be indicated by the absence of lakes in the closed basins that contain the dry lakes of Cadiz, Danby, and Bristol. Another factor that may have affected ground-water levels in the region was probable entrenchment of the Colorado River due to lowering of sea level. Lowering of the discharge level for ground water would tend to lower ground-water levels. The lower base level could have lowered the ground-water level and increased the ground-water gradient from the low ground-water divide southeast of Danby Lake to the Colorado River, but would have had negligible effect on ground-water level at Bristol and Cadiz Lakes. The time response is a significant factor in determining the water-level change during a different hydrologic regime. The ground-water-level response near basin fill will be dominated by the coarse-grained basin fill and will be relatively rapid. The response of ground water in most mountain ranges will be controlled by the hydraulic properties of the dominant crystalline metamorphic and igneous intrusive rocks and will be slower than in basin fills.

REFERENCES CITED

Bedinger, M.S., Langer, W.H., and Moyle, W.R., 1984, Map showing ground-water units, withdrawal, water levels, springs, and depth to ground water, Basin and Range province, southern California: U.S. Geological Survey Water-Resources Investigations Report 83-4116-A, scale 1:500,000, 1 sheet, 6 p.

Bedinger, M.S., Langer, W.H., and Reed, J.E., 1989, Hydraulic properties of rocks, *in* Bedinger, M.S., Sargent, K.A., Langer, W.H., Sherman, F.B., Reed, J.E., and Brady, B.T., Studies of geology and hydrology in the Basin and Range province, southwestern United States, for isolation of high-level radioactive waste—Basis of characterization and evaluation: U.S. Geological Survey Professional Paper 1370-A [in press].

Bedinger, M.S., Sargent, K.A., Langer, W.H., Sherman, F.B., Reed, J.E., and Brady, B.T., 1989, Studies of geology and hydrology in the Basin and Range province, southwestern United States, for isolation of high-level radioactive waste—Basis of characterization and evaluation: U.S. Geological Survey Professional Paper 1370-A [in press].

Brakenridge, G.R., 1978, Evidence for a cold, dry full-glacial climate in the American southwest: Quaternary Research, v. 9, no. 1, p. 22-40.

Busby, M.W., 1966, Annual runoff in the conterminous United States: U.S. Geological Survey Hydrologic Investigations Atlas HA-212, scale 1:500,000.

California Division of Mines and Geology, 1980, Geothermal resources of California: California Division of Mines and Geology Geologic Data Map 4, scale 1:750,000.

Durbin, T.J., and Hardt, W.F., 1974, Hydrologic analysis of the Mojave River, California, using a mathematical model: U.S. Geological Survey Water-Resources Investigations 17-74, 50 p.

Galloway, R.W., 1970, Full-glacial climate in the southwestern United States: Annals of the Association of American Geographers, v. 60, no. 2, p. 245-256.

Langer, W.H., Moyle, W.R., Jr., Woolfenden, Linda, and Mulvihill, D.A., 1984, Maps showing ground-water levels, springs, and depth to ground water, Basin and Range province, southern California: U.S. Geological Survey Water-Resources Investigations Report 83-4116-B, scale 1:500,000, 2 sheets, 6 p.

Metzger, D.G., and Loeltz, O.J., 1973, Geohydrology of the Needles area, Arizona, California, and Nevada: U.S. Geological Survey Professional Paper 486-J, p. J1-J54.

Mifflin, M.D., and Wheat, M.M., 1979, Pluvial lakes and estimated pluvial climates of Nevada: Reno, University of Nevada, Desert Research Institute, Center for Water Resources Research Technical Report Series H-W, Hydrology and Water Resources Publication 4, 53 p.

Olmsted, F.H., Loeltz, O.J., and Irelan, Burdge, 1973, Geohydrology of the Yuma area, Arizona and California: U.S. Geological Survey Professional Paper 486-H, 227 p.

Rantz, S.E., and Eakin, T.E., 1971, A summary of methods for the collection and analysis of basic hydrologic data for arid regions: U.S. Geological Survey open-file report, 125 p.

Reed, J.E., 1989, Mathematical model for simulating ground-water and heat flow, *in* Bedinger, M.S., Sargent, K.A., Langer, W.H., Sherman, F.B., Reed, J.E., and Brady, B.T., Studies of geology and hydrology in the Basin and Range province, southwestern United States, for isolation of high-level radioactive waste—Basis of characterization and evaluation: U.S. Geological Survey Professional Paper 1370-A [in press].

Rush, F.E., 1970, Regional ground-water systems in the Nevada Test Site area, Nye, Lincoln, and Clark Counties, Nevada: Nevada Department of Conservation and Natural Resources, Division of Water Resources, Water Resources-Reconnaissance Series Report 54, 25 p.

Sass, J.H., and Lachenbruch, A.H., 1982, Preliminary interpretation of thermal data from the Nevada Test Site: U.S. Geological Survey Open-File Report 82-973, 29 p.

Spaulding, W.G., 1984, Vegetation and climates of the last 45,000 years in the vicinity of the Nevada Test Site, south-central Nevada: U.S. Geological Survey Open-File Report 83-535, 199 p.

Thompson, T.H., Nuter, J.A., Moyle, W.R., and Woolfenden, L.R., 1984, Maps showing distribution of dissolved solids and dominant chemical type in ground water, Basin and Range province, southern California: U.S. Geological Survey Water-Resources Investigations Report 83-4116-C, scale 1:500,000, 2 sheets, 7 p.

MINERAL AND ENERGY RESOURCES

By B.T. Brady

Thirty-four metallic mining districts, or parts thereof, are located in the region (Wong, 1983). Small tonnages of ore, valued at less than a few million dollars, have been produced from numerous precious-metal and fewer base-metal deposits. Lode-gold mines have accounted for the principal production to date, and smaller contributions have come from base-metal and replacement deposits. A few dry gold placers were worked intermittently, and production generally was small. Nonmetallic or industrial mineral and rock occurrences are widely scattered throughout the region; excluding construction materials, none of these commodities have been produced on a sustained basis. In San Bernardino County, sodium chloride and calcium chloride have been produced from Bristol and Cadiz Lakes, and salt has been extracted from Danby Lake. Large identified resources of gypsum exist in eastern Riverside County. No coal occurrences or productive oil or gas pools have been identified in the study area.

METALLIC MINERAL RESOURCES

The names of the metallic mining districts described in this report are principally those delineated in plate 7 after Wong (1983), with supplemental information from Mardirosian (1974). The mining districts identify areas that have produced ore. These areas are not all inclusive and do not indicate the limit of mineralized rock. The principal metals produced from mines in the study area are gold, iron, manganese, copper, lead, silver, and zinc. Tungsten, mercury, titanium, uranium, vanadium, arsenic, and antimony occur in gangue minerals at a few locations. A summary of the important commodities and principal modes of occurrence for each mining district is listed in table 3.

Many of the metallic mineral deposits in the Sonoran region of California contain high- to moderate-temperature mineral assemblages that occur predominantly in fracture-controlled vein systems and less commonly in contact-metamorphic and replacement deposits. A few deposits contain ore in fissures and breccia zones. Precious and base-metal deposits occur in host rocks of Precambrian to Quaternary age. The most extensive deposits occur in the Picacho and Paymaster districts in eastern Imperial County. Many mines in the region are developed to depths of 107 m, and the Lum-Gray shaft in the Arica district is at least 305 m deep (Clark, 1970). The value and tonnage of ores produced from mines in the study area generally has been small.

Gold is the primary commodity produced from the metallic mineral deposits in the Sonoran region of California, and this metal occurs in mines in 27 of the 34 districts identified here. The principal sources of gold are narrow quartz veins, mainly in Precambrian granitic and metamorphic rocks. These lode-gold veins may be banded or brecciated, and locally are associated with diorite dikes. Iron oxides and pyrite, chalcopyrite, and varying quantities of other base-metal sulfides are common accessory minerals in these gold deposits. The Picacho mine, Imperial County, produced $2 million worth of gold from 1904 to 1910, and mines in the Chuckwalla district, Riverside County, and Halloran Spring and Old Dad districts, San Bernardino County, each yielded gold-bearing ores valued in excess of $100,000 (Clark, 1970). The principal deposits of placer gold are in the Potholes district, southeastern Imperial County. These dry placers were worked on a small scale by the Spanish explorers as early as 1775, and more than $2 million in gold was produced from these deposits between 1860 and early 1890 (Clark, 1970).

Base-metal sulfides occur in variable quantities in the majority of the mining districts in the Sonoran region of California. At least 45,000 kg of copper were produced from the Bell Gilroy lead-silver mine in the Providence Mountain district, the Von Trigger copper-gold mine in the Hackberry Mountain district, and the Piute gold mine in the Piute Mountain district, San Bernardino County, and from the Morning Star and Mountaineer gold mines in the Bendigo district, Riverside County (Eric, 1948).

An estimated 22,695 Mg of silver-lead ore were mined from the Paymaster, President, and Hazel workings in the Paymaster district, Imperial County (Morton, 1977). These mines were driven along a 1- to 13-m-wide, northeast-trending fissure vein at the contact between Precambrian gneiss and granite. The vein was explored for more than 1,200 m along strike and to a depth of at least 135 m (Morton, 1977).

The majority of the iron deposits in the study area are irregular lenticular masses of magnetite and hematite that occur as replacement bodies in Cambrian limestone or dolomite and are related to nearby granitic intrusions. The Vulcan mine on the western slope of the Providence Mountain area in San Bernardino County was estimated in 1944 to contain at least 5.4 million Mg of reserve-base ore, averaging more than 50 percent iron (Lamey, 1948). More than 2.4 million Mg of iron ore were mined from this property between 1942 and 1947 for

TABLE 3.—*Metallic mineral districts*

[Commodities are abbreviated as follows: Ag, silver; As, arsenic; Au, gold; Ba, barium; Cu, copper; F, fluorine; Fe, iron; Hg, mercury; Mn, manganese; Pb, lead; Sb, antimony; Ti, titanium; U, uranium; W, tungsten; Zn, zinc. Data from Wong (1983)]

Mining district	Commodities	Deposit type	Host rock	References
Imperial County				
Palo Verde	Mn, Ba, Fe	Fissure filling/vein	Pyroclastics, conglomerate, andesite, fanglomerate.	Bradley and others, 1918; Morton, 1977; Sampson and Tucker, 1942; Trask, 1950; Tucker, 1926.
Paymaster	Au, Ag, Cu, Pb, Zn, Mn, Fe, Ti.	Placer Contact Vein Fissure filling	Fanglomerate Schist, granite Gneiss, granite Conglomerate, andesite	Morton, 1977; Sampson and Tucker, 1942; Tucker, 1926.
Picacho	Au, Ag, Pb, Cu	Placer Breccia zone Vein/shear zone	Gravel Gneiss Schist, gneiss	Clark, 1970; Merrill, 1916; Morton, 1977; Sampson and Tucker, 1942; Tucker, 1926.
Pothole (southeastern Chocolate Mountains).	Au, Pb, Cu, Fe	Vein Placer	Gneiss, porphyroblastic metagranite. Gravel	Clark, 1970; Haley, 1923; Morton, 1977; Sampson, 1932; Sampson and Tucker, 1942; Tucker, 1919.
Riverside County				
Arica (Onward)	Au	Vein	Granite, schist	Clark, 1970; Saul and others, 1968.
Bendigo (Riverside Mountain).	Au, Ag, Pb, Fe, Cu, Mn.	Replacement Vein	Limestone, schist Granite, schist, limestone	Clark, 1970; Saul and others, 1968; Tucker and Sampson, 1945.
Big Maria Mountains area.	Au, Ag, Pb, Zn, Cu, Mn, Fe, W.	Replacement Gossan Vein	Diorite dike, limestone Dolomitic limestone Granite, schist	Saul and others, 1968; Tucker and Sampson, 1945.
Chuckwalla (Pacific).	Au, Ag, Pb, W, Cu.	Vein Contact	Granite, gneiss Diorite dike, schist	Clark, 1970; Saul and others, 1968; Tucker and Sampson, 1945.
Little Maria Mountains area.	Cu, W, Mn, F	Vein/shear zone	Schist, granite, quartzite, limestone.	Saul and others, 1968; Tucker and Sampson, 1945.
McCoy Mountains (Ironwood).	Au, Cu, Mn, U, Ag.	Vein	Schist, granite	Saul and others, 1968; Tucker and Sampson, 1945.
Mule Mountains (Hodges).	Au, Cu, Ag, Pb	Vein	Granodiorite	Clark, 1970; Saul and others, 1967; Tucker and Sampson, 1945.
Palen Mountains area.	Cu, Fe, Mn, F, Au.	Vein Contact metasomatic	Monzonite Limestone, granite	Saul and others, 1968; Tucker and Sampson, 1945.
San Bernardino County				
Arrowhead (Arrow).	Au, Cu, Ag, Pb	Vein	Diorite dike, quartz monzonite.	Clark, 1970; Wright and others, 1953.
Calumet	Au, Ag, Cu, Fe	Vein	Granite, gneiss	Wright and others, 1953.
Chubbuck	Au, Ag, Cu, Pb, Zn.	Vein	Schist, quartzite, marble, granitic rocks.	Wright and others, 1953.
Gold Reef	Au, W, Ag, Cu, Fe.	Vein Contact metasomatic	Andesite, gneiss, schist Limestone	Clark, 1970.
Granite Mountain area.	Fe	Replacement	Metamorphic and granitic rocks.	Wright and others, 1953.
Hackberry Mountain (Signal).	Au, Cu, V	Vein	Gneiss, schist	Clark, 1970; Wright and others, 1953.

TABLE 3.—*Metallic mineral districts*—Continued

Mining district	Commodities	Deposit type	Host rock	References
Halloran Spring.	Au, Cu, Ag, Pb, Fe, turquoise, alunite, pyrophyllite.	Vein Talc	Quartz monzonite, basalt, granite.	Clark, 1970; Wright and others, 1953.
Ibex	Au, Mn, Cu	Vein	Gneiss, schist	Wright and others, 1953.
Marble Mountain area.	Fe	Replacement	Marble	Wright and others, 1953.
Mopah Range area.	Au, Cu	Vein	Granite	Wright and others, 1953.
Old Dad (Solo)	Au, Cu	Vein	Gneiss, quartzite	Wright and others, 1953.
Old Woman (Danby).	Au, Pb, Zn, As, Ag, W, Cu, Hg, Sb.	Vein Contact metasomatic	Schist, quartzite, granite Limestone, granite	Clark, 1970; Wright and others, 1953.
Piute Mountain area.	Fe, Au, Ag, Pb, Zn, Cu, Hg.	Vein	Gneiss, schist	Bradley, 1918; Holmes, 1965.
Providence Mountain area.	Au, Ag, Pb, Fe, Cu.	Vein	Quartz monzonite	Wright and others, 1953.
Sacramento Mountain area.	Au, Ag, Cu, Fe, Hg.	Vwin	Gneiss, granite	Wright and others, 1953.
Sheep Hole Mountain area.	Au, Fe	Contact metasomatic Vein	Quartz diorite Granite	Wright and others, 1953.
Ship Mountain area.	Au, Cu, Ag, Fe	Vein	Limestone, granite	Wright and others, 1953.
Soda Mountains area.	Au, Ag, Cu	Vein	Granite	Wright and others, 1953.
Trojan (Providence).	Au, Cu, Ag, Pb, Zn, W, Fe.	Vein	Quartz monzonite	Clark, 1970.
Turtle Mountain area.	Au, Cu	Vein	Gneiss, schist	Wright and others, 1953.
Vanderbilt (New York).	Au, Ag, Pb, Cu, Zn.	Vein	Gneiss, pegmatite dike, granite, dolomite.	Clark, 1970; Wright and others, 1953.
Whipple (Cross Roads, Havasu Lake, Monument).	Au, Cu, Mn, Ag.	Vein Fissures, bedded.	Limestone, granite, fanglomerate.	Wright and others, 1953.

use in steel-mill blast furnaces. Additional iron deposits are in the Old Dad, Ship, Marble, and Granite Mountains, San Bernardino County; Chocolate Mountains, Imperial County; and Big Maria and Palen Mountains, Riverside County (Wright and others, 1953; Morton, 1977; Tucker and Sampson, 1945).

Manganese occurs widely and in several modes in the Sonoran region of California; however, the principal sources of manganese are several fissure-filling vein deposits in Tertiary basic volcanic rock and Quaternary fanglomerate in the Paymaster and Palo Verde districts, eastern Imperial County (Trask, 1950). More than 1.4 million Mg of manganese ore were shipped principally from these properties between 1953 and 1959 to support a Federally subsidized stockpile program (Morton, 1977). Manganese also has been noted in veins and shear zones with copper in the Big Maria and Little Maria Mountain areas, in copper-gold-silver ores in the McCoy and Whipple Mountains, and in copper-gold veins in the Palen Mountains and Ibex districts (Trask, 1950).

NONMETALLIC MINERAL RESOURCES

Barite, fluorite, and tremolite are the principal industrial minerals found in the Sonoran region of California. Barite is a common gangue mineral in many of the base-metal deposits discussed in this report, but no substantial deposits of barite are currently identified in the study area. Thin discontinuous fluorite veins are reported to occur in granitic rocks at the Providence Mountain property, on the eastern slope of the Granite Mountains, and in the Middle Camp prospect 10 km north of Halloran Springs, San Bernardino County (Crosby and Hoffman, 1951). In addition, two small irregular masses of tremolite are contained in layered schist and granite near the Middle Camp property. Nonmetallic industrial minerals or rocks, excluding building materials and natural aggregates, occur in a few scattered localities in the study area, but none of these deposits have sustained continuous production (Wright and others, 1953).

EVAPORITE DEPOSITS

Notable saline deposits are located in the playas at Bristol, Cadiz, and Danby Lakes, San Bernardino County. Bristol Lake contains numerous beds of halite interbedded with clay and siltstone. Salt layers are from a few tens of millimeters to at least 3 m thick, and alternating beds of evaporites and fine clastic sediments occur to depths of at least 862 m (Gale, 1951; Bassett and others, 1960). Halite was mined from near-surface beds that exceed 1 m in thickness, and more than 1.5 million Mg of salt were mined at Bristol Lake from 1912 to 1951 (Wright and others, 1953). In addition, an estimated 250,000 Mg of calcium chloride was produced from brines at Bristol Lake as a by-product of salt mining during the same period (Wright and others, 1953). The Bristol Lake and Danby Lake areas are classified as Known Leasing Areas (U.S. Bureau of Land Management, 1983).

The primary identified gypsum resources in the Sonoran region of California occur near the margins of Bristol and Danby Lakes, San Bernardino County, and in the Little Maria, Big Maria, and Palen Mountains, Riverside County. Near-surface deposits of gypsum were mined at the northwestern part of Bristol Lake, where gypsum was excavated to a depth of 1.8–2.4 m for more than 1.6 km along the outcrop. Mining at this location ceased in 1924, because of the existence of a shallow water table and the completion of rail transportation to the large gypsum deposits in the Little Maria Mountains (Wright and others, 1953; Ver Planck, 1952). Extensive gypsum deposits occur near Midland along the western and eastern flanks of the Little Maria Mountains and on the western side of the Big Maria Mountains. Gypsum at these locations occurs in fairly pure zones as much as 100 m thick and is interbedded with limestone and quartz-biotite schist. These deposits were the principal source of gypsum in California between 1925 and 1940 (Ver Planck, 1952).

Massive irregular beds of gypsum, as much as 30 m thick, are interbedded with severely deformed and faulted, metamorphosed sedimentary and igneous rocks in the northern Palen Mountains, Riverside County (Ver Planck, 1952). This deposit has not been developed extensively, and workings consist of several short adits and shallow open cuts. A large pre-Tertiary gypsum deposit is located on the eastern side of the Riverside Mountains 6.4 km south of Vidal, Riverside County. This gypsum deposit contains interbedded limestone and quartzite locally, and it extends southward into the Colorado River Indian Reservation. The gypsum-bearing zone is 30 m thick, crops out for more than 0.8 km, and contains an estimated 9 million Mg of very pure gypsum (Ver Planck, 1952; Tucker and Sampson, 1945).

A small tonnage of sodium sulfate was reportedly shipped in the early 1920's from a surface deposit at Danby Lake (Wright and others, 1953). Salts or nitrates of strontium, lithium, magnesium, and potassium have been reported in a few localities in the study area; however, no production has been reported to date for these commodities.

GEOTHERMAL RESOURCES

The Ford Dry Lake Known Geothermal Resource Area (KGRA) lies at the southern end of the Chuckwalla Valley about 53 km west of Blythe and is the only KGRA present in the Sonoran region of California. Geothermal waters with temperatures adequate for direct-heat uses occur in the study area near Desert Center and immediately west of Blythe, Riverside County. These two areas contain 24 wells less than 200 m deep, with water temperatures generally between 30 to 35 °C (Giessner, 1963a,b; Higgins, 1980).

COAL AND OIL RESOURCES

No coal occurrences have been identified in the Sonoran region of California (Brady, 1983). At least 10 wildcat boreholes have been drilled for oil in the study area in the eastern San Bernardino and Imperial Counties. Shows of oil have been reported in some of these exploration holes (California Division of Oil and Gas, 1981a, b), but no production has been reported to date.

REFERENCES CITED

Bassett, A.M., Kupfer, D.H., and Barstow, F.C., 1960, Core logs from Bristol, Cadiz, and Danby dry lakes, San Bernardino County, California: U.S. Geological Survey Bulletin 1045-D, p. 97–138.

Bradley, W.W., 1918, Quicksilver resources of California: California Divisions of Mines and Geology Bulletin 78, 389 p.

Bradley, W.W., Huguenin, Emile, Logan, C.A., Tucker, W.B., and Waring, C.A., 1918, Manganese and chromium in California: California Division of Mines and Geology Bulletin 76, 248 p.

Brady, B.T., 1983, Map showing coal deposits, oil and gas wells, seeps, and tar sandstone occurrences in the Basin and Range province: U.S. Geological Survey Open-File Report 83-549, scale 1:2,500,000, 101 p.

California Division of Oil and Gas, 1981a, Regional wildcat map WI-1: scale 1:63,360.

______1981b, Regional wildcat map WI-7: scale 1:250,000.

Clark, W.B., 1970, Gold districts of California: California Division of Mines and Geology Bulletin 193, 186 p.

Crosby, J.W., III, and Hoffman, S.R., 1951, Fluorspar in California: California Journal of Mines and Geology, v. 47, no. 4, p. 619-638.

Eric, J.H., 1948, Tabulation of copper deposits of California, *in* Copper in California: California Department of Natural Resources Division of Mines Bulletin 144, p. 199-357.

Gale, H.S., 1951, Geology of the saline deposits, Bristol Dry Lake, San Bernardino County, California: California Division of Mines Special Report 13, 21 p.

Giessner, F.W., 1963a, Data on water wells and springs in the Chuckwalla Valley area, Riverside County, California: California Department of Water Resources Bulletin 91-7, 77 p.

______1963b, Data on water wells and springs in the Rice and Vidal Valley areas, Riverside, and San Bernardino Counties, California: California Department of Water Resources Bulletin 91-8, 35 p.

Haley, C.S., 1923, Gold placers of California: California State Mining Bureau Bulletin 92, 167 p.

Higgins, C.T., 1980, Geothermal resources of California: California Division of Mines and Geology, scale 1:750,000.

Holmes, G.W., Jr., 1965, Mercury in California, in Mercury potential of the United States: U.S. Bureau of Mines Information Circular 82582, chap. 6, p. 87-206.

Lamey, C.A., 1948, Vulcan iron-ore deposit, San Bernardino County, California—Part G, *in* Iron resources of California: California Department of Natural Resources Division of Mines Bulletin 129, p. 87-95.

Mardirosian, C.A., 1974, Mining districts and mineral deposits of California (exclusive of oil, gas, and water): Laredo, Texas, Mineral Research Co., scale 1:1,000,000, 2 sheets.

Merrill, F.J.H., 1916, The counties of San Diego, Imperial, *in* 14th report for the State Mineralogist: California Mining Bureau, 113 p.

Morton, P.K., 1977, Geology and mineral resources of Imperial County, California: California Division of Mines and Geology County Report 7, 104 p.

Sampson, R.J., 1932, Placers of southern California: California Journal of Mines and Geology, v. 28, no. 2, p. 245-255.

Sampson, R.J., and Tucker, W.B., 1942, Mineral resources of Imperial County: California Journal of Mines and Geology, v. 38, no. 2, p. 105-145.

Saul, R.B., Gray, C.H., and Evans, J.R., 1968, Map of Riverside County, California, showing location of mines and mineral resources: California Division of Mines and Geology Open-File Release 68-7, 1:250,000.

Trask, P.D., 1950, Geologic description of the manganese deposits of California: California Division of Mines and Geology Bulletin 152, 378 p.

Tucker, W.B., 1919, Lassen County, *in* Mines and mineral resources of the counties of Butte, Lassen, Modoc, Sutter, and Tehama, 15th report for the State Mineralogist: California State Mining Bureau, p. 226-238.

______1926, Los Angeles Field Division (Imperial County), in 22nd report for the State Mineralogist: California State Mining Bureau, p. 248-285.

Tucker, W.B., and Sampson, R.J., 1945, Mineral resources of Riverside County: California Journal of Mines and Geology, v. 41, no. 3, p. 121-182.

U.S. Bureau of Land Management, 1983, California south half land classification status map: scale 1:500,000.

Ver Planck, W.E., 1952, Gypsum in California: California Division of Mines Bulletin 163, 151 p.

Wong, George, 1983, Preliminary map of the mining districts in the Basin and Range area of California: U.S. Geological Survey Open-File Report 83-95, 18 p.

Wright, L.A., Stewart, R.M., Gay, T.E., Jr., and Hazenbush, G.C., 1953, Mines and mineral deposits of San Bernardino County, California: California Journal of Mines and Geology, v. 49, nos. 1 and 2, 257 p.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1989—673-047/06,005 REGION NO. 8