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, Arizona

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1370–D

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

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

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CONVERSION FACTORS

For use of readers who prefer to use U.S. customary units, conversion factors for terms used in this report are listed below. U.S. customary units and troy weights are used in the "Mineral Energy Resources" section of this report because such terms are widely accepted and utilized by the mineral and energy fuel industries.

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)
	Acceleration	
milligal (mGal)	No Conversion	
	Volume	
liter (L)	0.2642	gallon (gal)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
	Flow	
liter per minute (L/min)	0.2642	gallon per minute (gal/min)
meter per day (m/d)	3.281	foot per day (ft/d)
	Temperature	
degree Celsius (°C)	9/5(°C) + 32 = °F	degree Fahrenheit (°F)
	Mass	
megagram (Mg) or metric ton	1.102	short ton (2,000 lb)
	Chemical concentration	
milligram per liter (mg/L)	About 1	part per million (ppm)

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, ARIZONA

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

ABSTRACT

The Sonoran region, southwestern Arizona, of the Basin and Range province, is south and east of the Colorado River. The structural basins typically are filled with 200 to 1,500 meters of clastic material with thick evaporite sections present locally. Basins of the region generally trend north-northwest. Relief between the valleys and adjacent mountains generally is 300 to 1,300 meters. Surface drainage is to the Colorado River, major tributaries being the Bill Williams and Gila Rivers. A few basins have interior or poorly integrated drainage.

Bedrock is exposed in about one-fourth of the region. Bedrock consists of Precambrian metamorphic and plutonic rocks, Paleozoic sedimentary rocks, Mesozoic volcanic and sedimentary rocks, and middle to late Tertiary volcanic and plutonic rocks. In addition to igneous tectonism, the rocks have been repeatedly deformed and moved along low-angle and steep faults. Present topography was largely shaped by Tertiary basin-and-range faulting, erosion, and deposition.

Potential host media for isolation of high-level radioactive waste in the Sonoran region, Arizona, include intrusive rocks, tuffaceous rocks, basaltic rocks, laharic breccias, and salt. Basin-fill deposits, and possibly other rock types, have potential as host media in the unsaturated zone.

Quaternary tectonism in the region is indicated in the northwestern and southern part of the region by relatively substantial strain release, epicenters of a few earthquakes with magnitudes greater than 4 (Richter scale, surface wave), and vertical crustal movement. Quaternary volcanic rocks may be present in the late Cenozoic volcanic field in the southeastern part of the region.

The Sonoran region is arid with annual precipitation less than 200 millimeters throughout most of the region and annual potential evaporation greater than 2.5 meters. Recharge of ground water occurs principally in areas of higher altitude where bedrock is permeable and by infiltration of mountain runoff in the basin areas. Discharge of ground water occurs by seepage to gaining streams, by evapotranspiration, by withdrawal from wells, and from springs. In most of the region, the concentration of dissolved solids in ground water is less than 500 milligrams per liter. Ground water near the Gila River and the Colorado River, however, contains 1,000 milligrams per liter or more dissolved solids. The ground water is mostly of the calcium magnesium or sodium bicarbonate type. Sulfate and chloride type waters occur in and near large discharge areas and in some playas.

Mineral development in the 19th century was confined to precious-metal lodes, base-metal vein and replacement ores, and placer deposits. More recent development has focused on large-scale, open-pit copper mines, which produce substantial quantities of precious metals as byproducts.

Manuscript approved for publication, January 10, 1985.

INTRODUCTION

By M.S. BEDINGER, K.A. SARGENT, and ROBERT B. SCARBOROUGH[1]

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, Langer, and others, 1989). The evaluation of the regions is given in Chapter H (Bedinger, Sargent, and Langer, 1990). The titles of chapters in this series are as follows:

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

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

[1]Arizona Bureau of Geology and Mineral Technology.

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).

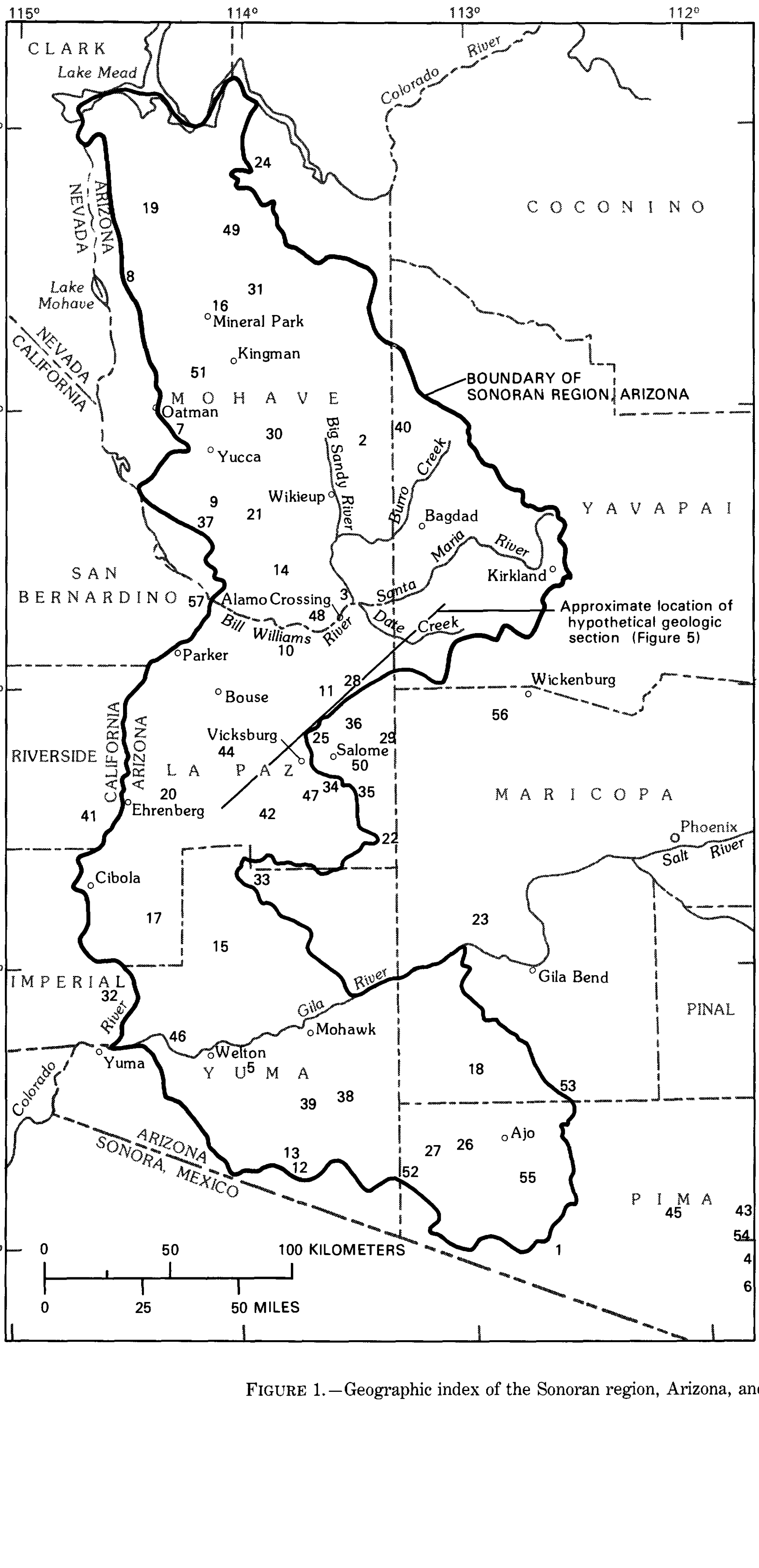
This report, characterization of the Sonoran region, Arizona, Chapter D, is one of six reports characterizing the geology and hydrology of regions in the Basin and Range province. Chapter D is divided into six separately authored sections: (1) Introduction, (2) Geology, (3) Potential host media, (4)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

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

The results of this study are not based on original data; no new field work was conducted specifically for this project. It is not intended to be a definitive report on the geologic and hydrologic aspects of the region, but it provides a general summary of published and unpublished data that are available. In parts of the region, inadequate data exist to characterize the area. In these places it was necessary to discuss the geologic or hydrologic characteristics in the vicinity of the region, and then project that data into the region.

GEOGRAPHIC SETTING

The Sonoran region, Arizona, is south and east of the Colorado River (pl. 1). The structural basins typically are filled with 200–1,500 m of clastic material with thick evaporite sections present locally. Bedrock pediments or shoulders of variable width are adjacent to the mountain blocks. Within the region, most basins trend north-northwest, except for the Butler and McMullen Valleys, which trend northeasterly in the central part of the area. The location of geographic features is shown in figure 1. Regional drainage-outlet areas are through the south- and west-flowing Big Sandy, Santa Maria, and Bill Williams Rivers in the north and the Gila River system in the south, which collectively drain into the south-flowing



EXPLANATION

1 AJO RANGE
2 AQUARIUS MOUNTAINS
3 ARTILLERY MOUNTAINS
4 BABOQUIVARI MOUNTAINS
5 BAKER PEAKS
6 BIG MARIA MOUNTAINS
7 BLACK MESA
8 BLACK MOUNTAINS
9 BUCK MOUNTAINS
10 BUCKSKIN MOUNTAINS
11 BUTLER VALLEY
12 CABEZA PEAK
13 CABEZA PRIETA MOUNTAINS
14 CASTANEDA HILLS
15 CASTLE DOME MOUNTAINS
16 CERBAT MOUNTAINS
17 CHOCOLATE MOUNTAINS
18 CRATER RANGE
19 DETRITAL VALLEY
20 DOME ROCK MOUNTAINS
21 DUTCH FLAT
22 EAGLETAIL MOUNTAINS
23 GILA BEND MOUNTAINS
24 GRAND WASH CLIFFS
25 GRANITE WASH MOUNTAINS
26 GROWLER MOUNTAINS
27 GROWLER WASH
28 HARCUVAR MOUNTAINS
29 HARQUAHALA MOUNTAINS
30 HUALAPAI MOUNTAINS
31 HUALAPAI VALLEY
32 IMPERIAL RESERVOIR
33 KOFA MOUNTAINS
34 LITTLE HARQUAHALA MOUNTAINS
35 MARTIN PEAK
36 MCMULLEN VALLEY
37 MOHAVE MOUNTAINS
38 MOHAWK MOUNTAINS
39 MOHAWK VALLEY
40 MOHON MOUNTAINS
41 MULE MOUNTAINS
42 NEW WATER MOUNTAINS
43 NORTH CAMOBABI MOUNTAINS
44 PLOMOSA MOUNTAINS
45 QUIJOTOA MOUNTAINS
46 RADIUM HOT SPRING
47 RANEGRAS PLAIN
48 RAWHIDE MOUNTAINS
49 RED LAKE PLAYA
50 "S" MOUNTAIN
51 SACRAMENTO VALLEY
52 SAN CRISTOBAL WASH
53 SAUCEDA MOUNTAINS
54 SOUTH CAMOBABI MOUNTAINS
55 VALLEY OF THE AJO
56 VULTURE MOUNTAINS
57 WHIPPLE MOUNTAINS

FIGURE 1.—Geographic index of the Sonoran region, Arizona, and vicinity.

lower Colorado River. Several basins have interior or poorly integrated drainages. Most basins are 150–300 m above sea level, and relief between valleys and adjacent mountains generally is 300–1,300 m. Bedrock probably is exposed in less than one-fourth of the total area.

ACKNOWLEDGMENTS

This chapter and the other chapters 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. Alternate member of the Province Working Group, H. Wesley Peirce of Arizona, contributed significantly to the regional phase of the study. The following individuals provided continued advice and assistance to the Basin and Range Province Working Group and in overall planning and execution of the work in preparation of this series of chapters: 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.

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GEOLOGY

By ROBERT B. SCARBOROUGH[2]

STRATIGRAPHY

PRECAMBRIAN ROCKS

Precambrian rocks are exposed locally beneath Cenozoic volcanic rocks in many parts of the Sonoran region, and extensively in the Cerbat and Hualapai Mountains in the northern part of the region. Precambrian rocks consist of plutonic rocks and metamorphic rocks of greenschist to amphibolite grade, 1.6–1.7 b.y. old, and porphyritic granite, 1.4 b.y. old (Wasserburg and Lanphere, 1965; Livingston, 1969; Anderson and Silver, 1971), all intruded by pegmatite and diabase dikes. Most crystalline terranes range in composition from granodiorite to granite, with minor diorite. A nonpervasive regional Precambrian foliation ascribed to the Mazatzal Revolution (Wilson, 1939) strikes north to east-northeast and generally dips steeply. Sedimentary rocks of late Precambrian age that occur in adjacent regions—for example, the Apache Group to the east, the Grand Canyon Supergroup to the northeast, and the Pahrump Group to the northwest in California—are not recognized in the Sonoran region of Arizona.

Bedrock geology consists of Precambrian crystalline and metamorphic rocks overlain by a sequence of Paleozoic cratonic-shelf sedimentary rocks, Mesozoic volcanic rocks and clastic sedimentary rocks, and Oligocene and Miocene volcanic and sedimentary rocks. In all but the extreme northeastern part of the Sonoran region, this assemblage of rocks has been repeatedly deformed and moved along low-angle and steep faults, and intruded by Mesozoic and Cenozoic plutons. Regionally, most of the Cenozoic section and some crystalline rocks beneath have been displaced to the northeast or southwest for unknown distances along middle Tertiary detachment faults. Reconstruction of major tectonic events is difficult because of extensive burial of all older rocks by upper Cenozoic basin-fill deposits.

There are both foliated and unfoliated Precambrian crystalline rocks exposed in the Hualapai and Cerbat Mountains. Elsewhere, as in the northern Black Mountains and in various ranges of Yuma, La Paz, and Maricopa Counties, many of the crystalline rocks are gneissic. Metamorphosed crystalline terranes that contain variably foliated and mylonitized Proterozoic gneisses and granites lie beneath regional detachment faults in the Buckskin, Rawhide, and Harcuvar Mountains and other ranges in the central part of the Sonoran region. Descriptions of Precambrian rock of the region are found in Gilluly (1946), Dings (1951), Thomas 1953), Kessler (1976), Anderson and Silver (1976), Stensrud and More (1980), and Howard and others (1982).

PALEOZOIC ROCKS

Small exposures of Paleozoic strata are known in some ranges of the region. These rocks, composed of limestone, dolomite, quartzite, and calcareous sandstone, have been described or mapped in the Plomosa, Harquahala, Little Harquahala, Rawhide, and Black Mountains and south of Ajo, in reports by Miller (1970), Reynolds and others (1980), Richard (1983), Shackelford (1976), and Wilson and others (1969). A comprehensive description of Paleozoic rocks in Arizona by Peirce (1976a) includes thicknesses in areas adjacent to the Sonoran region.

Paleozoic strata in the Sonoran region are correlated with: (1) The Bolsa Quartzite and Abrigo Formation of Cambrian age, the Martin Formation of Devonian age, and the Escabrosa Limestone of Mississippian age, which are cratonic in southeastern Arizona, and (2) the Supai Formation of Pennsylvanian and Permian age, and the Coconino Sandstone and Kaibab Limestone of Permian age, which are cratonic on the Colorado Plateau. Some workers correlate the Mississippian carbonate rocks with the Redwall Limestone of the Colorado Plateau. Only two complete and relatively unmetamorphosed Paleozoic sections are known in the Sonoran region southwest of the Colorado Plateau; these are in the southern Plomosa Mountains (Miller, 1970) and the Little Harquahala Mountains (Richard, 1983) as seen in figure 2. Virtually all other sections are tectonically attenuated and stratigraphically incomplete. Miller (1970) reports the following lithologies and thicknesses: Bolsa Quartzite—maroon, wavy bedded quartz sandstone, 21 m; Abrigo Formation—dark sandy shale with minor quartz sandstone beds, 50 m; Martin Formation—dolomitic limestone, dolomite, and sandy dolomite, 110 m; Escabrosa Limestone—dolomite, limestone, and cherty limestone, fossiliferous, 136 m; Supai Formation—quartzite, limestone, sandy limestone, and thin conglomerate, 180 m; Coconino Sandstone—white vitreous quartzite, eolian cross-bedding, 215 m; and Kaibab Limestone—chert-bearing limestone of various

[2]Arizona Bureau of Geology and Mineral Technology.

FIGURE 2.—Overturned Paleozoic section in the Martin Peak area of the Little Harquahala Mountains. View is to the northeast. Dark layered rocks on the right (A) are quartzite and calcareous quartzite correlated to the Supai Formation (Pennsylvanian and Permian). Light-colored rocks in the center (B) are correlated to the Redwall or Escabrosa Limestone of Mississippian age, and the darker units near the skyline on the left (C) may be Redwall, or Martin Formation of Devonian age. Section is near the southwestern end of a major northeast-trending belt of Paleozoic rocks, overturned to the southeast, that extends for more than 35 km through the Little Harquahala and adjacent Harquahala Mountains. Photograph by Stephen J. Reynolds, Arizona Bureau of Geology and Mineral Technology, 1981.

colors and minor gypsum-anhydrite in the upper part, fossiliferous, 220 m. Total aggregate thickness of 930 m is considered a minumum. As in other parts of Arizona, the Permian rocks are thicker than the rest of the Paleozoic combined (Peirce, 1976a).

Small Paleozoic masses, some of which are tectonically encased within crystalline rocks, are found in the Rawhide and Buckskin Mountains (Shackelford, 1980), the Plomosa Mountains (Miller, 1970; Scarborough and Meader, 1983), the southern Growler Mountains, the hills east of Parker, and at the extreme northern end of the Black Mountains (Wilson and others, 1969). Metamorphosed and deformed, but probably complete, Paleozoic sections are preserved beneath major thrust faults in the Harquahala and Granite Wash Mountains (Keith and others, 1982; Reynolds and others, 1980; Stephen J. Reynolds, Arizona Bureau of Geology and Mineral Technology, oral commun., 1984).

MESOZOIC ROCKS

Rocks of Mesozoic age in the Sonoran region of Arizona are represented by moderately sorted clastic sedimentary rocks with minor evaporites, volcanic rocks, Jurassic and Laramide plutons, and quartzose medium-grade metasedimentary rocks, all of which are variably metamorphosed. Jurassic volcanic rocks, part of the middle Mesozoic volcanic-arc complex of southwestern North America (Rogers and others, 1974; Coney, 1978) are recognized as intermediate to silicic flows and ash-flow tuff beneath Jurassic and Cretaceous sedimentary rocks in scattered localities in and around the Sonoran region (Damon and others, 1981, fig. 16). Jurassic granitic rocks are recognized in the northern Dome Rock Mountains (Reynolds, 1980) and in the Quijotoa, North and South Camobabi, and Baboquivari Mountains (Haxel and others, 1980). Clastic and volcanic sequences, locally as thick as 7 km, are found in the Dome Rock, southern

Plomosa, Buckskin, Granite Wash, Little Harquahala, and Harquahala Mountains (Robison, 1980; Reynolds, 1980; Harding, 1980). They are interpreted in part as having been deposited in a variety of terrestrial and lacustrine environments in a possible east-trending graben structure and then deformed and overridden by thrusts by Late Jurassic time (Harding, 1982; Harding and others, 1983).

Laramide plutons occur throughout Arizona Basin and Range country and are the source rocks for the region's important porphyry copper deposits at Mineral Park in the Cerbat Mountains of Mohave County (Wilkinson and others, 1982) and at Ajo in Pima County (Dixon, 1966). Sizable Laramide plutons also are present in the Little Harquahala and Granite Wash Mountains, around Wickenburg, and as a batholithic mass underlying most of the region from Ajo to Yuma. This batholith, termed the Gunnery Range batholith, is dominated by leucocratic granite and has an area of about 15,000 km^2 in Arizona; it has K/Ar ages of 53 m.y. (Shafiqullah and others, 1980). Dates on Laramide plutons in western Arizona generally cluster between 85 and 50 m.y.

A unit, probably correlative with the Orocopia Schist of Mesozoic(?) age of southern California, is recognized at three localities north of Yuma (Haxel and Dillon, 1978). The rocks are considered to be a regional allochthon composed of graywacke, chert, marble, and ultramafic rocks metamorphosed to greenschist or amphibolite grade in Late Cretaceous and Paleocene time. Their tectonic setting is incompletely known. No Cretaceous volcanic rocks are recognized in the Sonoran region (Reynolds, 1980; Shafiqullah and others, 1980); however, many undated Mesozoic rocks are known in the region.

CENOZOIC ROCKS

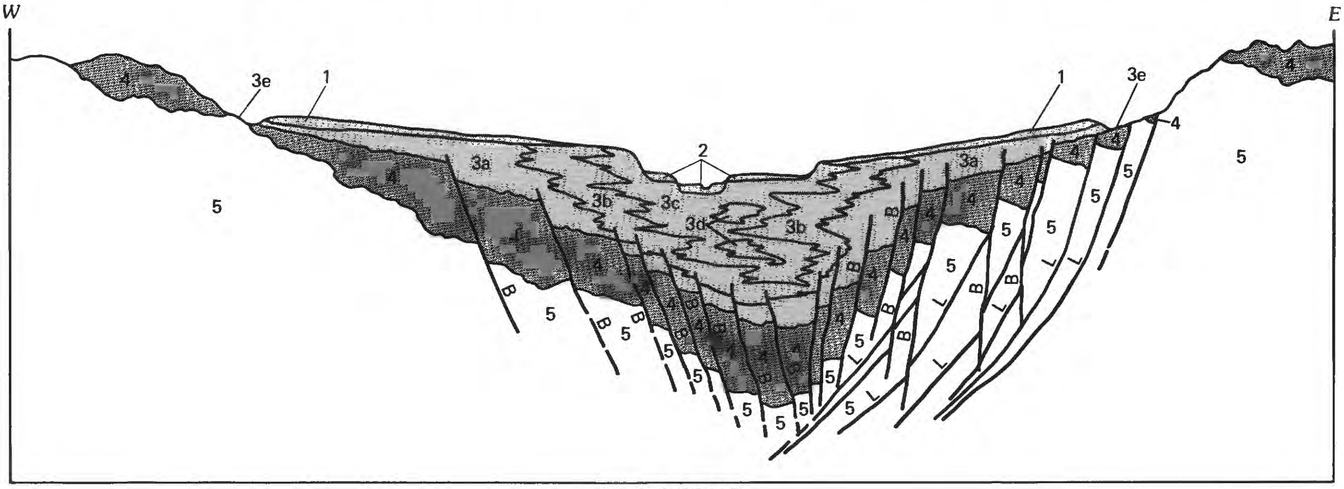
Older Cenozoic rocks in western Arizona are characterized by a diverse, 30–13-m.y.-old assemblage of middle Tertiary volcanic rocks, presumed buried subvolcanic plutons, and volcaniclastic sedimentary rocks. This assemblage is unconformably overlain by locally thick basin-fill sediments and sparse intercalated basalt flows, formed in response to rift tectonics (younger than 13 m.y.) of the Basin and Range disturbance (Shafiqullah and others, 1980).

The middle Tertiary assemblage in the Sonoran region is characterized (Eberly and Stanley, 1978; Wilt and Scarborough, 1981) by a tripartite succession of: (1) Older fluvial and eolian redbeds with subordinate ash flows and tuff, commonly dominated by debris flows and mud flows; (2) an overlying locally thick volcanic sequence with ash flows, andesite, and pyroclastic sediments grading upwards into commonly less deformed basaltic andesite; and (3) a capping sequence of fluvial and lacustrine rocks that contain coarse redbeds and uraniferous organic-enriched lakebeds. The middle Tertiary volcanic-sedimentary succession may attain an aggregate thickness of as much as 2,000 m (Eberly and Stanley, 1978, fig. 8) but is not uniform in thickness throughout the region. The upper part of the sequence contains significant low-grade uranium deposits in some middle Miocene carbonaceous lacustrine sediments in the Date Creek basin that is at the northern end of the Harcuvar Mountains (Sherborne and others, 1979). Other nearby valleys also contain middle Miocene, uraniferous, fine-grained sediments buried under basin fill (Wilt and Scarborough, 1981).

The boundary between the middle Tertiary tripartite sequence (Eberly and Stanley, 1978, Unit I of their fig. 3) and the younger post-basin-and-range basin-fill sediments and basalts (Unit II of their fig. 3) is a " *** widespread unconformity surface resulting from an important period of subsidence, block-faulting, and erosion that began in Miocene time (13 to 12 m.y. ago)" (Eberly and Stanley, 1978). Basin-fill sediments are as much as 1,700 m thick where drilling has penetrated pre-basin-fill rocks (Eberly and Stanley, 1978). Peirce (1976b) suggests that as much as 3,300 m of basin fill occurs in the Hualapai Valley south of Red Lake, based on geometry of tilting of the Cerbat Mountains and gravity studies. The Bouse Formation is an assemblage of limestone, sandstone, and claystone deposited in a Pliocene estuary environment along most of the lower Colorado River.

Thick accumulations of middle Tertiary volcanic rocks that survived the subsequent basin-and-range block faulting and that remain part of exposed range blocks are found in the Black, Aquarius, and Mohon Mountains of Mohave and Yavapai Counties, the Chocolate, Castle Dome, Kofa, New Water, Eagletail, and Gila Bend Mountains of La Paz and Yuma Counties, and the Crater Range and Sauceda Mountains of Maricopa County. Prominent late-stage, middle Tertiary, potassic, basaltic andesite fields are found surrounding the Mohon Mountains of Mohave County, in the Chocolate, Kofa, and Eagletail Mountains of Yuma County, in the Gila Bend Mountains of Maricopa County, and as a series of mesa-capping units east of Ajo, Pima County.

Basin-and-range basalts, less than 13 m.y. old, are found as a few relatively thin caps on small mesas in the northern Black Mountains of Mohave County, a 130-km^2 mesa cap in northernmost La Paz County, the Sentinel volcanic field (600 km^2) in western Maricopa County, and the northernmost part of the Pinacate volcanic field of Yuma County. The youngest basalts in the Sonoran region of Arizona are between 2 and 6 m.y. old in the Sentinel field; however, Pliocene and Pleistocene flows



NOT TO SCALE

EXPLANATION

GENERAL DESCRIPTION OF ROCK UNITS–

1 Pleistocene piedmont alluvial fans, capping a beveled pediment that was eroded into basin-fill sediments. Fans thicken and contain coarser debris mountainward

2 Late Pleistocene and Holocene strath-terrace gravel, sand, and overbank silt, related to erosion-backfill cycles of the valley's trunk stream. These landforms and deposits are better developed in valleys nearer the Colorado and Gila Rivers

3 Basin fill, generally interpreted as less than 13 million years old
- 3a Proximal-alluvial-fan facies (poorly sorted sand and gravel)
- 3b Distal-fan facies (gravelly sand, sand, silt, and air-fall ash)
- 3c Lacustrine facies (bedded clay, silt, gypsum stringers, air-fall ash, and diatomites as pods)
- 3d Evaporite facies (halite, anhydrite, and clay stringers)
- 3e Stripped pediment exposed at the mountain fronts within valleys undergoing stream erosion. Basin-fill deposits thin and coarsen mountainward, and rest on the pediment that is eroded into older Tertiary deposits and bedrock

4 Mid-Tertiary volcanic rocks, and sediments, generally 28-13 million years old. Individual units generally lack lateral continuity. Volcanic rocks consist of welded and unwelded ash-flows, andesite and basalt flows, agglomerate, tuff, and intrusive domes. Sediments are heterogeneous assemblage of redbeds, fluvial sand, and lacustrine clay, silt, and limestone

5 Pre-Cenozoic bedrock, including Precambrian crystalline and metamorphic rocks, Paleozoic limestone and sandstone, and Mesozoic volcanic rocks, volcaniclastic rocks, redbeds, and sandstone

Unit I of Eberly and Stanley (1978)

Unit II of Eberly and Stanley (1978)

CONTACT

FAULT–Dashed where approximately located. B, basin and range faults, high-angle normal, active during block faulting; L, listric (curviplanar) faults, active during denudational tectonics

FIGURE 3.—Hypothetical geologic section transverse to main drainage across a typical basin.

are found in the Pinacate field of Sonora and southernmost Yuma County, just south of the study area (Shafiqullah and others, 1980).

A thick sequence of predominantly halite in the Sonoran region has been penetrated in the subsurface south of Red Lake playa in Hualapai Valley (Peirce, 1976b). Geophysical modeling indicates a mass with a width of 8 km, length of 18 km, and bottom depth of 3.2 km (1,220 m of this sequence has been drilled). Possible volume is 250–500 km^3. The salt probably represents closed-basin accumulation under nonmarine conditions during the Miocene (Peirce, 1976b).

Basin-fill geology is a major factor in characterization of regional hydrology. Sand and gravel facies within basin fill are the most permeable of all near-surface units in the Basin and Range province, and hence their spatial distribution is important in formulating ground-water traveltimes. A hypothetical geologic section that shows most facies relationships recognized in a typical southern Arizona basin is given in figure 3. Basin-and-range faults that commonly are transmissive near the surface may be much less permeable at depth because of overburden pressure and silicification or alteration of fault zones related to fossil geothermal systems.

SUMMARY OF GEOLOGIC EVENTS

PRECAMBRIAN TECTONICS

The Precambrian basement that extends throughout the Sonoran region records an older Precambrian (1.7–1.6 b.y. ago) island-arc volcanic and submarine sedimentary terrane (including banded iron-formations; Gilmour and Still, 1968), that was intruded by a series of granites and subjected to a nonpervasive metamorphism (Wilson, 1939; Anderson, 1951; Anderson and others, 1971; Conway, 1976; Shafiqullah and others, 1980). Regional schistosity produced by this metamorphism generally trends northeast as do central Arizona fold belts and ore-deposit clusters. This orogeny, termed the Mazatzal Revolution by Wilson (1939), is represented by the Bamori Schist, Vishnu Schist, Yavapai Schist, and Pinal Schist terranes throughout the State of Arizona and was attributed to regional accretionary tectonics by Shafiqullah and others (1980). Attendant greenstone belts and volcanogenic massive sulfide deposits in central Arizona were discussed by Stensrud and More (1980), Donnelly and Hahn (1981), and Anderson and Silver (1976).

This metamorphosed terrane was intruded by regionally extensive batholiths dated at 1.4–1.45 b.y. (Silver, 1968). Plutonic rocks of the batholiths are composed of moderately alkalic granite and quartz monzonite characterized by the presence of rapakivi-type orthoclase phenocrysts ("megacrysts"), and, in one location in the Aquarius Mountains, pods of high-grade radioactive carbonatite material. This intrusive episode is termed "anorogenic" in reference to the apparent absence of related volcanic rocks or evidence of associated deformation (Silver and others, 1977; Anderson, 1983).

Based on data from areas north and east of the Sonoran region, the region was eroded to low relief after the 1.4-b.y. granite metamorphism, and younger Precambrian sedimentary rocks of the Apache Group, Grand Canyon Supergroup, and Pahrump Group were deposited in a nearshore sedimentary environment, perhaps related to a North America–Siberia continental rifting (Stewart, 1976a, 1976b; Sears and Price, 1978; Condie, 1982). Main lithologies of the Apache Group include quartz sandstone, tuffaceous siltstone, maroon shale, black carbonaceous shale, and minor conglomerate. Late-stage, rift-related sills and dikes of diabase and minor syenite intruded the sedimentary rocks throughout central Arizona at about 1,100–1,200 m.y. ago (Silver, 1960; Livingston, 1969). Sedimentation occurred between 1,420 and 1,100 m.y. ago. Some diabase dikes, presumably of this age, intrude the crystalline terrane of the Hualapai Mountains (Kessler, 1976) and the Mohave Mountains (Nakata, 1982).

PHANEROZOIC TECTONICS AND VOLCANISM

Paleozoic Tectonics

The Arizona Paleozoic cratonic assemblage is hypothesized to have been deposited throughout the Sonoran region, although most Paleozoic rock occurrences there are now limited to a few sparse, generally deformed, ductilely attenuated masses. Peirce (1976a) and Schumacher and others (1976) suggested that Paleozoic crustal movements in Arizona primarily were epeirogenic, consisting of mild tilting induced by broad regional arching and sagging. Stone and others (1983) concluded that the cratonic Paleozoic section appears to have been deposited throughout the Sonoran region and westward to the central Mojave Desert in California about 300 km west of this region.

Mesozoic and Cenozoic Denudation

The Sonoran region is characterized by Oligocene and younger volcanic and sedimentary rocks deposited on Precambrian and lower Tertiary crystalline and metamorphic basement and locally on areas of Paleozoic through Eocene strata. On the adjacent Colorado Plateau, a northeast-dipping basal Tertiary erosion surface, which has been incised progressively downward through the Paleozoic section to the southwest, is capped along the plateau edge with Tertiary gravels (rim gravels), derived from the southwest. Farther east along the plateau edge, a northeast-sloping Cretaceous (pre-Turonian) surface also truncates progressively older Paleozoic strata to the southwest. These conditions indicate that the part of the Basin and Range province bordering the plateau was topographically higher than the plateau and was largely stripped of its Mesozoic and Paleozoic sedimentary cover by later Mesozoic and early Tertiary erosion that preceded the intense middle Tertiary volcanic pulse (Peirce and others, 1979). This central Arizona Mesozoic highland was termed the Mogollon Highland by Harshbarger and others (1957) and by Cooley and Davidson (1963). It evidently was a southwestern source for Mesozoic and lower Tertiary sediments on the southern Colorado Plateau. Subsequently, the Mogollon Highland was lowered in altitude relative to the plateau as a consequence of some combination of further erosion and tectonic effects, mostly during Eocene and Oligocene(?) time, with subsequent regional drainage disruption and creation of new Basin and Range drainage trends. This newly created, post-"rim gravel" erosion cycle and the earlier Mesozoic erosion of the Highland were jointly responsible for the removal of nearly all the Phanerozoic cover from an area extending some unknown distance southwest of the plateau edge. Cretaceous erosion largely preceded Laramide tectonism and magmatism in southern Arizona; the middle Tertiary loss of altitude was contemporaneous with, and probably the consequence of, major crustal extension and associated volcanism in the Basin and Range province.

The modern Mogollon Rim, the southwestern edge of the Colorado Plateau, was erosionally carved into crystalline rocks by the newly created Oligocene(?) basin-and-range drainages as they eroded northeastward in an area of southwestward pinchout of resistant Paleozoic and Jurassic strata under the Cretaceous surface (Young and Brennan, 1974; Peirce and others, 1979; Shafiqullah and others, 1980).

It is not known how far to the southwest this erosion occurred; the complex tectonism southwest of the metamorphic core complexes disturbs the record so that the relative effects of erosion and tectonism in that region are not clear.

Pre-Laramide Mesozoic Tectonism

The lowermost Mesozoic deposits known in the Sonoran region are middle Jurassic felsic volcanic rocks found in a zone 200 km wide, extending southwest from Parker. These are typically overlain by a series of locally thick Jurassic or Cretaceous clastic sedimentary rocks or both. One of the more regionally recognized sequences, the McCoy Mountains Formation, has been described in a west-northwest-trending graben (Harding, 1982).

Regional thrust-faulting occurred after the deposition of Jurassic and Cretaceous volcanic and sedimentary rocks, followed by the intrusion of some early Laramide (85 m.y.) plutons. Rocks juxtaposed by thrust faults are found from the Rawhide Mountains southward to near the Yuma area and southeastward, to the area east of Ajo. These thrust sequences consist of stacked tectonic plates of Precambrian metamorphic and plutonic rocks, Paleozoic sedimentary rocks, and Mesozoic sedimentary and volcanic rocks. The bounding faults are at some locations that are nearly flat, as in the Harquahala Mountains (Reynolds and others, 1980) and in the Little Harquahala Mountains (Richard, 1983), shown in figure 4, and at other locations the faults are moderately to steeply dipping, as in the southern Plomosa Mountains (Miller, 1970) and the northern Dome Rock Mountains (Harding, 1982). Plates composed of crystalline rocks appear to have had little internal deformation in comparison to structurally confined plates composed of Paleozoic and Mesozoic rocks that commonly contain tight to isoclinal, and in some places recumbent, folds, that indicate attenuation and extensive ductile deformation. Kinematic indicators of this thrust deformation in the Sonoran region of Arizona indicate an older southeast-vergent transport and a younger south-southwest or north-northeast transport (Reynolds and others, 1980; Stephen J. Reynolds, oral commun., 1984). Shackelford (1976) indicates the presence of probable Cretaceous northeast-thrusting, thermal metamorphism, and penetrative deformation of Precambrian and Paleozoic rocks in the Rawhide Mountains. Hamilton (1982) suggests that a pre-80–90-m.y.-old northeast overfolding with attendant metamorphism affected the rocks of the Big Maria Mountains in nearby southeastern California. Miller and McKee (1971) noted west-vergent thrusts in the southern Plomosa Mountains that juxtaposed a complex array of Precambrian, Paleozoic, and Mesozoic rocks in an hour-glass-shaped, east-dipping thrust pile. Directly to the east is a nonmetamorphosed terrane that contains one of the two relatively complete fossiliferous Paleozoic sections in western Arizona. The other relatively complete Paleozoic section is illustrated in figure 2. Scarborough and Meader (1983) mapped a thrust stack in the northern Plomosa Mountains that records a ductile, knappelike deformation that produced an attenuated, imbricately faulted, south-dipping Paleozoic and Mesozoic plate overlain and underlain by Precambrian crystalline plates. East- or northeast-vergent minor folds occur in the plate, which is intruded by a postkinematic pluton dated at 85 m.y. by K/Ar (biotite). Outcrops of Mesozoic(?) Orocopia Schist mapped by Haxel and Dillon (1978) north of Yuma, may be exposed in windows through a regionally extensive thrust plate that may include the entire southern part of the Sonoran region.

This late Mesozoic thrust terrane extends from at least as far south as the southern Dome Rock Mountains, and perhaps as far as Yuma, northward to the Rawhide and Buckskin Mountains, westward into the eastern Mojave Desert, and eastward at least to the Harquahala Mountains. The terrane is thought by some to be a continuation of the Sevier orogenic belt of western Utah and southern Nevada (Armstrong, 1968). Unlike the Sevier belt, however, these thrusts involve surficial crystalline rocks and ductilely attenuated Phanerozoic sedimentary rocks which are both southeast and northwest vergent (Burchfiel and Davis, 1975; 1981; Dickinson and Snyder, 1978; Carr, 1983).

The east-trending belt containing the 4-km-thick Jurassic(?) McCoy Mountains Formation trends through the Dome Rock and southern Plomosa Mountains of the Sonoran region of Arizona (Harding, 1982). This belt has been deformed into an oppositely dipping pair of folds partly cored with McCoy Mountains sedimentary rocks that are surrounded by Jurassic volcanic rocks. Moderate north- and south-dipping faults juxtapose this belt into a lower plate position with respect to the terranes to the north and south that do not contain thick

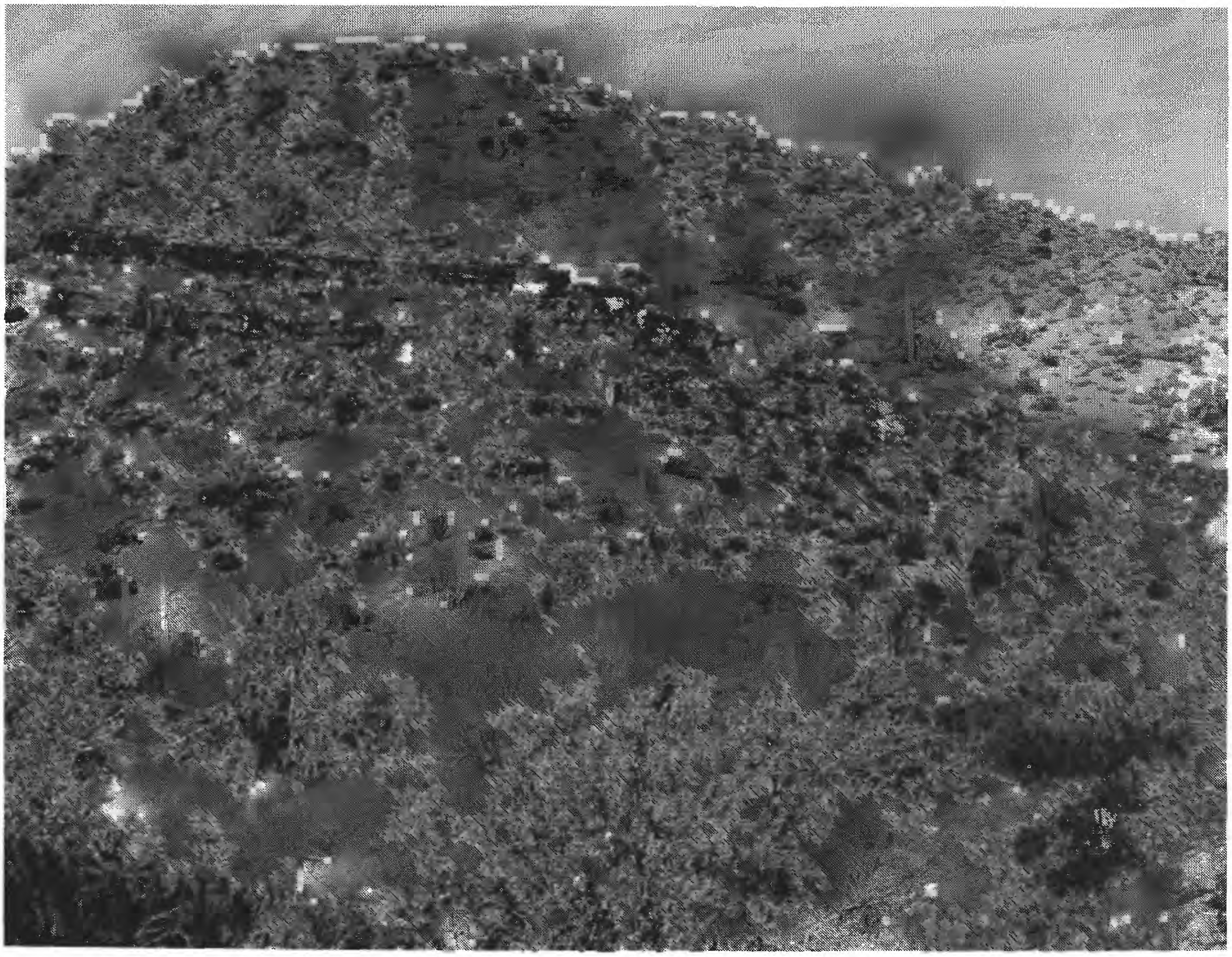


FIGURE 4.—Hercules thrust fault, exposed near "S" Mountain, southeast of Salome, La Paz County. The ledge-forming unit consists of quartzite and stretched-pebble conglomerate of Mesozoic age, correlated with the McCoy Mountains Formation (Harding, 1982). The unit is capped by the gently dipping Hercules thrust and overlain by sheets of light-colored leucocratic granite and gray quartz diorite of Precambrian or Mesozoic age. Beneath the ledge-forming unit is quartz-feldspar schist derived from Mesozoic volcanic rocks and volcaniclastic sediments. The Hercules thrust fault has been mapped in the Harquahala, Little Harquahala, and Granite Wash Mountains. This thrust terrane is intruded elsewhere by undeformed granite (85 m.y. old) of the Tank Pass pluton. Photograph by Stephen J. Reynolds, Arizona Bureau of Geology and Mineral Technology, 1981.

Mesozoic clastics. Harding (1982) calls the northern terrane, Cratonic North America; the central terrane, the McCoy terrane; and the southern region, the Mojave-Sonora composite terrane. The deformation of the belt was suggested by Harding and others (1983) to have taken place in Jurassic time, based on paleomagnetic evidence. Preliminary structural analysis from the northern fault complex, the Boyer Gap thrust, indicated south-vergent movement, which placed cratonic rocks over McCoy terrane rocks (Yeats, 1984). Tosdal (1982) noted a possible continuation of the southernmost of the two bounding faults, the Mule Mountains thrust, from the Mule Mountains of California to the southern Dome Rock Mountains of Arizona, based on similar juxtapositions along a south-dipping reverse fault.

Possible pre-Sevier strike-slip faulting is hypothesized by Silver and Anderson (1974) and Anderson and Silver (1981). This fault or series of faults is termed the Mojave-Sonora megashear and is interpreted to have a northwest trend. About 800 km of left-lateral offset has been indicated based on: (1) An offset pattern of radiometrically dated Precambrian rocks in Arizona and California, and Sonora, Mexico; (2) plate-tectonic modeling of the opening of the Caribbean Sea (Anderson and Schmidt, 1983); and (3) Mesozoic pinchout patterns in Sonora. The zone has been drawn through an area just west of Ajo and the lower Colorado River near Ehrenberg, La Paz County, Ariz. If the fault exists, dissimilar Precambrian through Middle Jurassic rocks should be juxtaposed across the line.

Laramide Orogeny

The Laramide orogeny in southern and western Arizona is represented by a period of intense subduction-related magmatism and volcanism, significant copper-molybdenum-lead-zinc-silver-gold metallogenesis, and late-stage northeast-directed compressional tectonics (Coney, 1976, 1978; Keith and Barrett, 1976; Drewes, 1978; Damon and others, 1981; Titley, 1981, 1982; Keith, 1982).

Laramide plutons with related porphyry-copper mineralization appear to have been emplaced into structurally high crust, and localized along structural intersections related to Precambrian fabric (Titley, 1981). Some evidence exists to indicate that Laramide lead-zinc-silver vein-type mineralization and copper-molybdenum porphyry-type deposits were associated with late Mesozoic shallowing subduction (Coney and Reynolds, 1977; Keith, 1978, 1981). Some workers now believe that a subsequent Eocene magmatic-tectonic event occurred that was related to, or possibly the culmination of, the Laramide orogeny as shown by a direct relationship between magmatic metallogenic space-time patterns and inferred paleosubduction geometries (Keith, 1978, 1981, 1982; Shafiqullah and others, 1980). The possibility has been suggested (Keith, 1981) that the subduction zone reached highest crustal levels (slightest dip angles) during the Eocene at which time crustal anatexis and high-level shearing produced plutonized tectonite basement that eventually became locally arched and formed the core of the exposed southern Arizona metamorphic-core complexes. Alternatively, some workers view the ductile basement shearing as due to regional distention during the middle Tertiary, unrelated to the Laramide orogeny (Reynolds, 1980).

Laramide dikes in the Sonoran region strike generally northeast to east, indicative of an overall regime of northeast compression (Rehrig and Heidrick, 1976). In the Vulture Mountains, dikes, which are probably related to the 68-m.y.-old Wickenburg batholith, itself elongate in a northeastern direction, generally trend northeast as well. At Bagdad, dioritic dikes that transect the 71-m.y.-old mineralizing stock trend east-northeast. Andesite dikes at Ajo strike nearly eastward.

Metamorphic Core Complexes and Middle Tertiary Detachments

In the Sonoran region, metamorphic core complexes, as defined by Rehrig and Reynolds (1980), Davis (1979), and Davis and others (1980), are found in the Buckskin, Rawhide, and Harcuvar Mountains, near the western terminus of a northwest-trending zone, which is 600 km long in Arizona and California and contains a number of such complexes. The core-complex rocks contain a distinct rock assemblage and are separated from "normal" geology by a low-angle fault (Coney, 1980, fig. 2). Beneath the fault, the lower plate assemblage consists of mixed crystalline rocks subjected to Late Cretaceous(?) to middle Tertiary mylonitization, heating, and deformation by ductile shearing within a subhorizontal shear couple. The intensity of lower plate mylonitization increases upward through a thin zone that is characterized by a chloritized breccia and capped by a ledge-forming microbreccia and overlying fault surface, commonly referred to as a detachment fault. The mylonitic zone usually continues structurally downward through the lower plate crystalline rocks for less than a kilometer. The mylonitic zone contains a mineral lineation in the foliation plane that is interpreted as being parallel to and produced by upper plate transport during mylonitization. This lineation direction is usually at right angles to the strike direction of upper plate, tilted Cenozoic strata, an observation that led some workers (Rehrig and Reynolds, 1980; Rehrig and others, 1980) to infer that mylonitization and detachment represent ductile and brittle aspects, respectively, of the same phenomenon, namely a crustal-scale shear zone that accommodated major extension across the Basin and Range province.

Detached (upper plate) rocks located structurally above the core complexes range in age from Precambrian to Miocene. Upper plate Cenozoic strata near the core complexes usually consist of Oligocene sequences and younger, early to middle Miocene strata that typically have a consistent regional direction of strike (northwest) and dip (northeast or southwest). The Miocene rocks usually are less deformed than the older upper plate rocks, indicating episodic deformation. Regionally, upper plate volcanic rocks as young as 15 m.y. were involved in rotation and detachment faulting (Scarborough and Wilt, 1979; Rehrig, 1982; Rehrig and others, 1980; Suneson and Lucchitta, 1979). In the lower plate, the radiometric ages of all mylonitized rocks have been thermally changed to early or middle Cenozoic. Unlike lower plate rocks, upper plate rocks have radiometric ages that have not been affected by Tertiary thermal effects. This history indicates that the mylonitic zone has been subjected to a substantial thermal flux. A hypothesized geologic section through the northeastern end of the Harcuvar metamorphic core complex (fig. 5) shows the lower and upper plate relationship and the detachment fault. The vertical exaggeration of 10 makes the fault, which actually dips 20°, appear nearly vertical.

This geologic section is a part of one of 32 constructed for the Sonoran Desert region for this study; these sections are on open file at the Arizona Bureau of Geology and Mineral Technology in Tucson, Ariz.

The section crosses two detachment faults that separate lower plate thrust-juxtaposed rocks or mylonitic crystalline rocks with postkinematic plutons from upper plate allochthonous, but thermally intact, Precambrian crystalline and Tertiary volcanic rocks. Northeast transport of upper plate rocks is indicated by antithetic southwest rotation of upper plate volcanic rocks throughout the region, as seen in the section, and hence, a postdetachment arching of the detachment faults and also of some mountain ranges is indicated. It is not known whether the master detachments continue to dip at moderate angles to great depths, or if they are simply flat faults, now warped so that they intersect the land surface at different places.

The complete residual Bouguer gravity profile above the section, from Lysonski and others (1981), indicates a 10-mGal negative anomaly in the Ranegras Plain and a nearly 30-mGal negative anomaly in this part of the Date Creek basin, indicative of the depths to bedrock as shown. Dense evaporite facies in basin fill and thick, dense, buried Tertiary volcanic rocks make interpretation of depth to crystalline bedrock difficult without subsurface control.

Detachment-fault outcrops and lower plate mylonitic fabrics together define two sets of large-scale, foldlike irregularities in the Sonoran region. In the Harcuvar, Buckskin, Rawhide, and possibly the Harquahala Mountains, one of these fold sets is well defined and has axes trending east-northeast. Synforms and antiforms are represented by sediment-filled valleys and archlike ranges, respectively. The sinusoidal form of the detachment fault and mylonitic fabrics is readily discernible on geologic maps of the area (Rehrig and Reynolds, 1980). The arches are thought to be somehow related to mylonitization and detachment faulting because their axes are parallel to the movement direction on the detachment fault and to mineral lineation in the mylonites, but the precise origin of the arches is unknown.

A second, broader warp has a northwest-trending axis that is orthogonal to the east-northeast arches and perpendicular to detachment-fault movement direction. It appears to have formed as a result of isostatic rebound after tectonic denudation (Rehrig and Reynolds, 1980; Spencer, 1984). The plunging axes at the ends of some of the arches in the Harcuvar complex reflect this warp, as might the overall regional northwest trend of the Arizona southeast California line of core complexes. In the Lincoln Ranch basin area of the Buckskin Mountains, a northwest-trending, southwest-vergent reverse fault places Precambrian gneisses over middle Miocene redbeds (Wilson, 1962, pl. 24). It is possible to relate this thrusting to the formation of the northwest-trending arch or warp.

Rotated Cenozoic strata also are found well away from the core complexes throughout western Arizona and eastern California; these strata consistently strike northwest and dip either southwest or northeast. Tilted volcanic strata in the Cabeza Prieta Mountains are shown in figure 6. It is now assumed, but not proven, that these terranes were subjected to detachment movement contemporaneously with movement of upper plate rocks around the core complexes.

Strata with uniform northeast or southwest dip directions, as seen in figure 6, can be grouped into elongate belts that extend through western Arizona in a northwest direction parallel to the Colorado Plateau margin (Rehrig and Heidrick, 1976; Scarborough and Wilt, 1979; Rehrig and others, 1980; Stewart, 1980). The belts, 100 km or more wide, were interpreted by Rehrig and others (1980) as brittle upper plate expansive regimes between narrow northwest-trending zones (belt boundaries) of concentrated lower plate ductile expansion and magmatic ingress into high crustal levels. Similarly Stewart (1980) suggested the belts are related to stress relief extending outward from boundaries of zones that are interpreted as initial sites of rupture during late Cenozoic extension. Klein (1982) suggested the existence of a zone, 30 km wide, containing a positive residual aeromagnetic anomaly that parallels the tilt domain boundaries that extend through the Parker area. He suggested a crustal, magnetic-source region at least 6 km below the land surface and noted that the magnetic zone separates the terrane to the northeast that has a relatively positive residual-gravity signature from the terrane to the southwest that has a negative residual-gravity signature. Perhaps this magnetic anomaly signifies the presence of one of the zones of concentrated lower plate ductile expansion of Rehrig and others (1980).

The depths to which the basal detachment faults extend are not known. In some areas, such as the detached terrane including the Whipple Mountains of east-central California, available evidence based on reconstructing upper plate thicknesses indicates that detachment faults dipped gently to depths of 10–15 km at the time of formation (Howard and others, 1982). Wernicke (1981) has proposed that basalt detachments continue at moderate dip angles through the entire lithosphere. It is not known how many different detached terranes are present in the Sonoran region. Because there are at least four different dip domains present in the Sonoran region (Scarborough and Wilt, 1979, fig. 28),

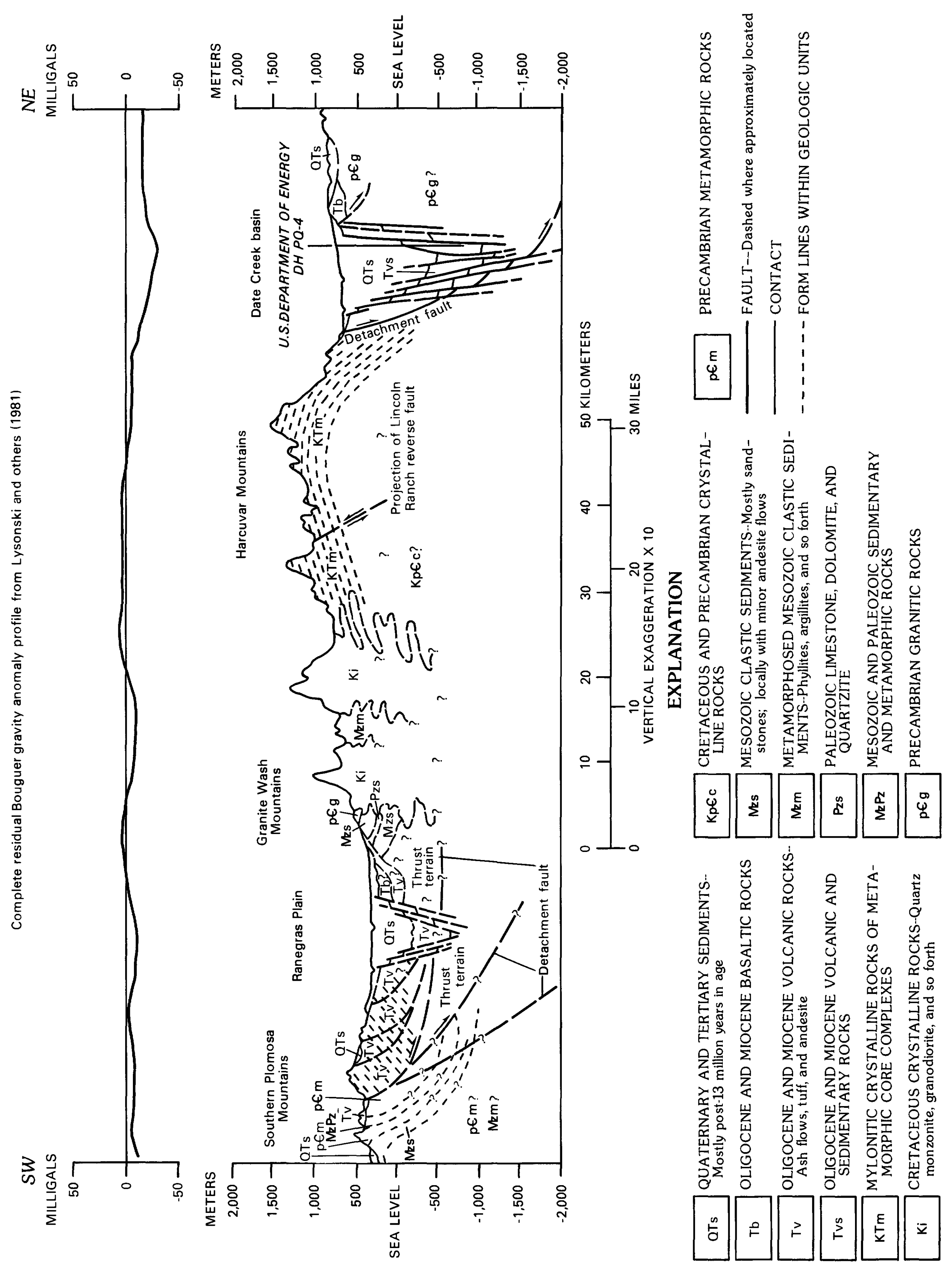


FIGURE 5.—Hypothetical geologic section through the southern Plomosa and Harcuvar Mountains.

FIGURE 6.—Southern Cabeza Prieta Mountains (Yuma County) looking north-northeast nearly parallel to the strike of tilted, dark, bedded volcanic rocks and pyroclastic sediments. Underlying rocks include Mesozoic(?) schist and granite of the 53-m.y.-old Gunnery Range batholith. The uniform 25° northeast dip of the strata may be explained by southwest transport on a series of northwest-striking, listric, normal faults that affected the volcanic rocks and underlying crystalline bedrock. The high point on the skyline is Cabeza Peak. Beyond the mountains lies Mohawk Valley. View is taken from about 1.6 km south of Cabeza Peak. Photograph by Peter Kresan, University of Arizona, 1980.

each presumably having moved in response to distention along an individual master detachment fault, there may be several, or even numerous, large-scale, low-angle faults in the region.

The Gila trough is adjacent to and parallels an anomalous east-northeast regional photolinear trend occupied by reaches of the Salt and lower Gila Rivers. This trend extends from Yuma through Phoenix and continues at least as far as the Mazatzal Mountains (80 km northeast of Phoenix). The origin of the trough between Yuma and Phoenix is unknown although it appears to be an elongate series of depocenters partly filled with relatively thick middle Tertiary sedimentary and volcanic rocks (Eberly and Stanley, 1978) and, hence, is inferred to have been forming during that time. Its form has been described as a graben or half-graben (Eberly and Stanley, 1978) and as a synform or downwarp (Pridmore and Craig, 1982). Along the southern flank of the trough, detached middle Tertiary redbeds at Baker Peaks, which probably were deposited in the trough, contain indications of northward sediment transport from the volcanic-free Gunnery Range batholith terrane located to the south. These rocks have a northeast trend of detachment movement as indicated by their general southwest dips, a trend that approximately parallels the long axis of the trough (Pridmore and Craig, 1982). The east-northeast trend of the trough and the trend of upper plate detachment movement along its flanks appears geometrically analogous to that of the line of northeast-trending, arched-core complexes and intervening synformal valleys in the Buckskin-Harquahala region to the north, which also have indicated northeast tectonic transport (southwest dips) of upper plate rocks.

Miller and McKee (1971) discuss a west-northwest-trending zone of strike-slip faults in the southern Plomosa Mountains that disrupt rocks as young as some middle Tertiary volcanic rocks that contain a flow 20 m.y. old. Apparent left-lateral separation of 6 km is dispersed across a zone 8 km wide that contains at least three large-offset faults. It is not clear whether this faulting is related more to detachment faulting or to later basin-and-range pull-apart rhombochasm basin development (Davis and others, 1980); Anderson and others, 1972). Curiously, this strike-slip trend is parallel to the strike of upper plate rotated strata in the immediate region that have been deformed by west-northwest-striking, listric normal faults of about the same age.

Middle Tertiary Volcanism

The middle Tertiary volcanic episode in the Sonoran region is believed to have been related to subduction (Coney and Reynolds, 1977). It consisted of earlier andesite-rhyodacite, ash-flow tuff volcanism and penecontemporaneous sedimentation in local basins, followed by deposition of a voluminous mass of dacite-latite-rhyodacite ash-flow tuff, and finally by extrusion of a volcanic series dominated by potassic basaltic andesite with local ultrapotassic trachyte (Shafiqullah and others, 1980). Later andesite and ash flows of the Growler Mountains are illustrated in figure 7. Local variations of this sequence are known, such pre-ash-flow basaltic volcanism in the Castaneda Hills (Suneson and Lucchitta, 1983). The middle Tertiary rock suites in the Sonoran region range in age from about 28–15 m.y., at which time an abrupt change to basaltic volcanism took place (Eberly and Stanley, 1978; Shafiqullah and others, 1980; Suneson and Lucchitta, 1983). Local volcano-tectonic processes consisted of differential block subsidence with local landsliding and sedimentation as noted in the southern Black Mountains (Thorson, 1971) and in the Mohave Mountains (Pike and Hansen, 1982). Pike and Hansen (1982) suggest that most volcanic and sedimentary rocks lack lateral continuity because of numerous unconformities produced by coeval volcano-tectonic processes. Thick successions of ash-flow tuff and concentrated faulting, possible indicators of calderas, are found in the southern Black Mountains (Thorson, 1971) and in the Kofa and Castle Dome Mountains and the Ajo Range. Detailed studies in the latter three areas are lacking.

As summarized in Zoback and others (1981), the beginning time of middle Tertiary volcanism progressed westward from New Mexico (40 m.y. ago) to east-central California (25 m.y. ago) in keeping with the post-Eocene, steepening Benioff zone that was discussed by Coney and Reynolds (1977). Middle Tertiary volcanism lasted about 10–14 m.y. in any given area.

Middle Tertiary dikes in the Sonoran region generally trend northwest and are nearly orthogonal to Laramide dikes in the region (Rehrig and Heidrick, 1976; Nakata, 1982; Howard and others, 1982). Quartz-monzonite porphyry dikes at Bagdad strike north-northwest. In the Vulture Mountains, extensive rhyodacite to latite porphyry dikes, 15–18 m.y. old, trend north-northwest. The Tertiary dike trend in both the Castle Dome and Mohave Mountains is northwest. In the southern Black Mountains, rhyolite porphyry dikes and associated banded quartz-calcite epithermal gold-silver veins trend northwest to west-northwest. The general north-northwest dike trend in middle Tertiary time (25–15 m.y. ago) generally is thought to be perpendicular to the direction of tectonic extension during the middle Tertiary magmatic episode.

Basin-and-Range Faulting and Volcanism

Basin-and-range faulting, as characterized by Eberly and Stanley (1978) and Zoback and others (1981), has affected the southwestern one-half of Arizona. Basin-and-range mountain blocks in the Sonoran region trend north to north-northwest. In contrast, the Buckskin, Rawhide, Harquahala, and Harcuvar Mountains trend east-northeast but appear to be a manifestation of undulatory northeast-trending Tertiary (Miocene?) arching that has profoundly affected the form and surface distribution of mylonitic rock of the metamorphic core complexes. Hence, these ranges that trend differently are not believed to be basin-and-range fault blocks.

Most of the high-angle, nonrotational horst-and-graben faulting generally has been bracketed in time as younger than 13 m.y. and older than 5 m.y. throughout most of the southern part of the Basin and Range province (Stewart, 1971; Anderson and others, 1972; Scarborough and Peirce, 1978; Eberly and Stanley, 1978; Zoback and others, 1981). Where investigated by seismic methods and drilling, most basins morphologically resemble either nonrotated wedge-shaped sags downdropped along one or more steep, planar normal faults or prism shapes above tilted bedrock ramps that are displaced by moderately to deeply penetrating, listric(?) normal faults (Stewart,

FIGURE 7.—View northwestward towards the southern Growler Mountains (A) of western Pima County in the distance, which are capped by dark, gently eastward dipping middle Tertiary volcanic strata. All dark rocks are Oligocene and Miocene andesite, basalt, and ash flows. Basement rock of Mesozoic(?) granite is exposed in the small, irregularly shaped gray hill (B). Growler Wash (C) drains nearly 700 km^2 of the Valley of the Ajo, out of view to the right. This drainage joins San Cristobal Wash downstream, and together they empty into the Gila River at the Mohawk Mountains 100 km downstream. Most of the scene is in T. 14 S., R. 7 W. Photograph by Peter Kresan, University of Arizona, 1981.

1978; Eberly and Stanley, 1978; Zoback and others, 1981; Anderson and others, 1983). In addition, most basins are filled with from 600 m to perhaps 1,500 m of basin-fill sediments (fig. 3). However, it is not clear to what degree the present-day structural relief between range tops and adjacent basin bottoms is the result of high-angle block faulting or of other events such as local isostatic rebound of denuded terrane after detachment faulting (Spencer, 1984). New evidence indicates that many western Arizona range blocks, including some outside the line of metamorphic core complexes, are bounded just at the mountain fronts by detachment faults that now appear to have steeper dips than at the time of detachment, indicating postdetachment relative uplift or arching of the range blocks. The northeast-trending arches that affected the metamorphic core complexes of the Sonoran region produced minimum, vertical structural relief of 1,200 m on the mylonites, which is a significant fraction of that postulated for the southeastern Arizona, range-top to basin-bottom relief of 1,800–3,300 m (Scarborough and Peirce, 1978).

Depth to bedrock within the basins has been modeled using the residual Bouguer-gravity anomalies by Oppenheimer and Sumner (1980). Peirce (1976b) suggested the presence of 3,000 m of basin fill, including a significant fraction of halite thickness, for Hualapai Valley south of Red Lake (fig. 8). Large residual anomalies that indicate depth to bedrock possibly as great as 2,500 m (Scarborough and others, 1983) are found in the valleys west of the Cerbat Mountains, west of the southern Black

FIGURE 8.—Red Lake playa (A) in the Hualapai Valley in Mohave County. View is to the northeast towards the Grand Wash Cliffs (B), composed of Precambrian crystalline rocks overlain by Paleozoic strata as young as Devonian. In the low foreground are hills at the base of the Cerbat Mountains (C). The farthest skyline, just visible, consists of cliffs of Permian sandstone and limestone that form the Mogollon Rim (D), the physiographic edge of the Colorado Plateau. Although Red Lake retains water for short intervals after storms, no Pleistocene pluvial record of the lake is known. A large body of halite (at least 1,200 m thick and possibly 150 km^3 in volume) is known in the subsurface south (to the right) of the playa. Throw on the Grand Wash fault, parallel to the valley edge on the far side of the playa, may be as great as 4,900 m. Photograph by Peter Kresan, University of Arizona, 1980.

Mountains, east of the Mohave and Buck Mountains, east of the southern Castle Dome Mountains, and between Baker Peaks and the Mohawk Mountains, as shown in figure 9.

The northern block of the Hualapai Mountains has been downthrown 350 m since 18 m.y. ago with respect to the Colorado Plateau edge, based on present altitudes of the Miocene Peach Springs Tuff (Young and Brennan, 1974) on both sides of the Hualapai Valley and on the hypothesis that the ash-flow sheet flowed northeasterly from a now-buried source west of Kingman down into canyons already incised into the edge of the Colorado Plateau (Young and Brennan, 1974). However, Precambrian crystalline rocks in the Cerbat Mountains north of Kingman are now found at least 760 m higher than corresponding rocks beneath the Paleozoic strata at the plateau edge. These observations indicate that, although Basin and Range grabens formed by subsidence, adjacent range blocks need not have been vertically shifted any great distances during basin-and-range faulting. Peirce (1976b) suggests a total vertical throw of 4,900 m on the Grand Wash fault just north of the Peach Springs Tuff outcrops at the western edge of the Colorado Plateau. The throw was distributed in unknown proportions between earlier rotational faulting and later basin-and-range faulting but still left the Precambrian crystalline rocks of the Cerbats 760 m higher than their position beneath Paleozoic strata at the plateau edge.

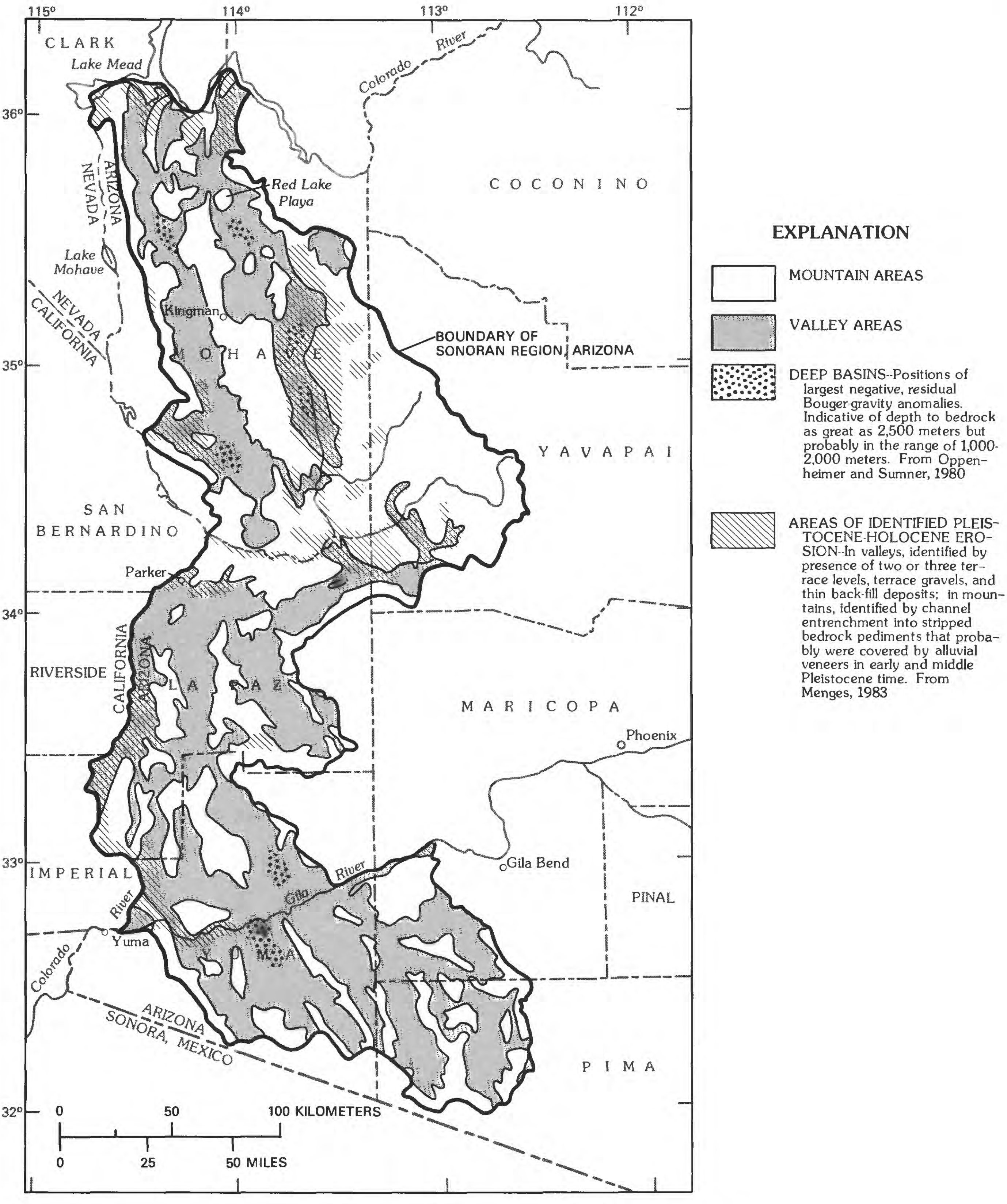


FIGURE 9.—Deep basins and areas of Pleistocene and Holocene erosion.

Zoback and others (1981) suggest that total Cenozoic Basin and Range crustal extension may be as much as 100–300 percent, although the extension during the late high-angle block faulting may be only 10–30 percent; the rest may be assumed to have occurred during middle Tertiary time.

Coinciding with the change of tectonic style from low-angle detachment to high-angle block faulting is a change in volcanic-rock chemistry (Rehrig and others, 1980; Shafiqullah and others, 1980). Volcanism older than 15 m.y. is subduction related; is dominated by andesite, silicic ash flows and tuff and some basaltic andesite; and is characterized by strontium-isotope initial ratios in the 0.707–0.709 range. Volcanism younger than 15 m.y. throughout Arizona is dominated by alkali basalts that have characteristically large titanium contents, and strontium initial ratios of 0.704–0.705, indicative of mantle-derived, relatively uncontaminated magmas. The statewide distribution of basalt-dominated volcanic rocks younger than 15 m.y. is depicted on a map by Scarborough and others (1983).

Miocene, Pliocene, and Quaternary History

An incursion of the Gulf of California into the lower Colorado River trough in response to the opening of the Gulf of California in late Miocene and Pliocene time (Karig and Jensky, 1972) is postulated to explain the deposition of the estuarine-fluvial Bouse Formation from near Yuma to as far north as the Lake Mohave area (Smith, 1970; Eberly and Stanley, 1978; Lucchitta, 1979). The almost impermeable basal limestone of the Bouse Formation is a subsurface marker horizon in the region, and presumably affects ground-water flow characteristics. Thickness of the Bouse Formation ranges from several meters along valley flanks to a few hundred meters in the southern part of the region around Yuma (Metzger and others, 1973). Present altitudes of the top of the formation indicate post-Bouse crustal warping of about 2,400 m between the southwestern corner of Arizona and the Lake Mohave area (Lucchitta, 1979; Blair, 1978). The downwarping of the Bouse Formation south of Yuma probably is related to continued Gulf of California rift tectonics; the postulated Bouse uplift in the Lake Mohave region has an unknown tectonic source.

A series of lacustrine, gypsiferous, red-brown clays that interfinger with or predate the Bouse Formation were penetrated in the subsurface in most, if not all, of the valleys along the lower Colorado and lower Gila–Salt Rivers (Ross, 1923; Eberly and Stanley, 1978). Eberly and Stanley (1978) suggested that the clays were products of the same period of Basin and Range interior drainage that produced the massive evaporites in the basins farther east (fig. 3). The clays usually are overlain by Pleistocene sand and gravel along valley axes and by piedmont gravel along mountain fronts, indicating a progressive development of the modern Colorado-Gila drainage system in post-Bouse time. Although aspects of the modern drainage pattern had undoubtedly been evolving through the Tertiary, the through-flowing Colorado and Gila River systems apparently began to form some time between 10 and 5 m.y. ago, based on evidence of closed-basin, nonmarine halite accumulation older than 10.5 m.y. in the Luke basin near Phoenix (Eberly and Stanley, 1978) and on interior drainages older than 5.9 m.y. in the Lake Mead area (Lucchitta, 1979; Eberly and Stanley, 1978).

Several cycles of intermittent river incision and stabilization occurred through the last part of the Pleistocene. Areas where river incision, terrace formation, and pediment stripping have been the most pronounced are shown inbut no evidence of Pleistocene pluvial lakes are recognized here or elsewhere in the Sonoran region of Arizona (Williams and Bedinger, 1984) either because they did not form in Hualapai Valley or other basins which may have been closed, or possibly because the easily eroded and abraded character of the Pleistocene surficial silt and sand in the valleys did not facilitate preservation of the shorelines.

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POTENTIAL HOST MEDIA FOR RADIOACTIVE WASTE

By K.A. SARGENT

Host media considered to have potential for isolation of high-level radioactive waste in the Sonoran region, Arizona, include intrusive rocks, such as granite and other coarse-grained plutonic rocks; ash-flow tuff, especially where densely welded and greater than 100 m thick; basalt and basaltic andesite lava flows, where greater than 100 m thick; and salt. Other, less abundant rock types that have potential may occur in the region. These include laharic and mudflow breccia and certain shallow intrusive bodies such as rhyolite domes. The occurrence and thickness of argillaceous sedimentary and metasedimentary rocks was summarized by Johnson (1984). Argillaceous rocks of the Sonoran region are folded, faulted, and deformed; they appear to have little or no potential as host rock in the region. In addition to the above mentioned rock types, basin-fill deposits and possibly other rock types have potential as host media in the unsaturated zone. The outcrop areas of potential host media and areas believed to have thick unsaturated zones in the Sonoran region, Arizona, are shown in plate 2.

INTRUSIVE ROCKS

Granitic rocks are widespread in the Sonoran region of Arizona. In some areas, granitic rocks form the entire cores of the mountain ranges; elsewhere the granitic rocks are sheared and have overridden younger rocks in the upper plates of detachment faults. The distribution, age, and lithology of the granitic rocks of the region were summarized by Johnson and Scarborough (1984a).

Ground-water units SA–01 and SA–02 and the western part of ground-water unit SA–03 are underlain by the extensive, Tertiary and Cretaceous Gunnery Range batholith. Elsewhere in ground-water unit SA–03 are Precambrian and late Mesozoic to early Tertiary granitic rocks. These granitic rocks crop out in mountain ranges and probably underlie Quaternary and Tertiary basin fill at relatively shallow depths. The granitic rocks are mostly leucogranite and quartz monzonite, which locally are extensively fractured and foliated.

The rare granitic rocks that crop out in ground-water units SA–04 and SA–05 are Mesozoic to Tertiary granite and quartz diorite. Granite and quartz monzonite, of Precambrian, Mesozoic, and early Tertiary age, are widespread in the mountain ranges of ground-water unit SA–06. Granitic stocks that occur in the core complexes of the Harquahala Mountains in the eastern part of ground-water unit SA–06 are believed to be underlain by shallow thrust faults.

In ground-water unit SA–07 the intrusive rocks are granite, quartz monzonite, and quartz diorite, mostly of Precambrian age with some of Mesozoic and Tertiary age. Granite occurs as younger Precambrian and Mesozoic stocks intruding older Precambrian granite. Of special interest is a large body of Precambrian gabbro and anorthosite in the vicinity of Bagdad.

Ground-water units SA–08, SA–09, and SA–10 contain Precambrian granite, granodiorite, and quartz monzonite, that have intruded older Precambrian granitic rocks. A few Cretaceous and Tertiary granitic stocks intrude Precambrian gneissic and granitic rocks.

TUFFACEOUS ROCKS

Tuffs of widespread occurrence include ash-flow tuff, some interbedded tuffaceous sedimentary rocks, and ash-fall tuff, with minor rhyolitic lava flows. Welded tuffs generally are thin and mixed with other volcanic rocks. For details on distribution and description of individual occurrences, the reader is referred to Jenness and others (1984).

Mixed volcanic rocks consisting of ash-flow tuff, volcanic sedimentary rocks, and rhyolitic and andesitic lava flows and breccia occur in ground-water units SA–02 to SA–05. Ash flows of middle Tertiary age are as much as 100 m thick in ground-water units SA–04 and SA–05. Tuffs and lavas of Cretaceous age in the northeastern part of ground-water unit SA–03 are deformed and fractured.

Mixed volcaniclastic rocks of middle Tertiary age occur in the central part of ground-water unit SA–06. The thickness of these rocks generally is unknown, although thick tuffs are reported in the Eagletail Mountains in the easternmost part of ground-water unit SA–06.

Ground-water unit SA–07 contains mostly thin ash-flow deposits of rhyolitic composition. However, southwest of Bagdad, the Grayback Mountain Rhyolite Tuff of Late Cretaceous(?) or early Tertiary(?) age is as much as 150 m thick. Ground-water units SA–08, SA–09, and SA–10 contain outcrops of ash-flow tuffs complexly mixed with agglomerate, and andesitic, rhyolitic, and basaltic lava flows. Dated ash flows are 17–18 m.y. old, about the age of inception of the basin-and-range faulting. These, as well as other ash flows in the area, are thin, generally less than 50 m.

BASALTIC ROCKS

Basalt flows are widespread and of middle to late Tertiary age, contemporaneous with basin-and-range faulting. For details on distribution and descriptions of individual occurrences, the reader is referred to Johnson and Scarborough (1984b).

In ground-water units SA–01 to SA–06, most of the basalts are 10–20 m.y. old (Miocene) and are olivine basalts and basaltic andesites. Maximum aggregate thickness is 400 m in the Lomosa Mountains and 450 m near Ajo; individual flows are no more than 15–20 m thick. In ground-water unit SA–07 upper Tertiary olivine basalt, basaltic andesite, and interbedded clastic rocks are no more than 100 m thick. Ground-water units SA–08, SA–09, and SA–10 have scattered upper Tertiary basalt and andesite flows. Individual flows generally are 3–10 m thick, but some flows in the Miocene Mount Davis Volcanics are greater than 75 m thick. Flows commonly are interbedded with tuffaceous sedimentary rocks.

SALT

Large salt deposits occur in Hualapai and Detrital Valleys, in the northern part of the Sonoran region of Arizona (Peirce, 1981a; Ege, 1985). The Red Lake deposit, beneath Hualapai Valley, is buried by more than 450 m of sedimentary cover. Geophysical modeling indicates the halite body to be 8 km wide, 18 km long, and probably 3.2 km thick. A drill hole has penetrated 1,220 m of salt. Peirce (1981b) reported that a natural-gas storage facility is planned for the Red Lake salt. The Detrital Valley salt deposit occurs south of Lake Mead. It is buried by as much as 600 m of sedimentary fill and is as much as 335 m thick. The Detrital Valley salt is associated with gypsum, anhydrite, and clastic sediments belonging to the Muddy Creek Formation of Miocene and Pliocene age. Other deep valleys in western Arizona may contain thick salt or other evaporitic bodies that are unknown at this time.

OTHER ROCKS

Metamorphosed and unmetamorphosed Mesozoic sedimentary rocks, Precambrian metamorphic rocks, Quaternary basalts, and basin-fill material are present in the Sonoran region of Arizona. Generally these rocks are not considered potential host rocks and were not discussed separately. However, some metamorphic rocks, mainly granite gneiss, were mapped with the granite because of their close spatial relationship to, and similar lithologic properties with the granitic rocks. Quaternary basaltic rocks locally are extensive, but because their age indicates relatively recent tectonic activity they are not considered host rocks. Basin fill is considered as potential host rock in the following section on the unsaturated zone.

UNSATURATED ZONE

With the exception of ground-water unit SA–07, the ridges in the region are believed to contain unsaturated sections as thick as 150 m. Basin fill contains as much as 150 m of unsaturated Quaternary and Tertiary sediment in the Sacramento Valley (ground-water unit SA–08), Hualapai Valley (SA–09), Detrital Valley (SA–10), Dutch Flat (SA–07 and SA–08), and Date Creek (SA–07).

Volcanic rocks generally are above the water table and because they are relatively permeable, they are considered satisfactory for potential host rocks in the unsaturated zone. However, their thickness probably is great enough only locally to provide a site for a repository in the unsaturated zone.

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QUATERNARY TECTONISM

By K.A. SARGENT and ROBERT B. SCARBOROUGH[3]

Quaternary tectonism of the Sonoran region, Arizona, is indicated by the seismicity, heat flow, Quaternary faulting, late Cenozoic volcanic activity, and vertical movement of the region. Each of these features is depicted in figure 10.

SEISMICITY

Fewer than 30 earthquakes were reported for the Sonoran region of Arizona in a regional compilation by Algermissen and others (1983). Two earthquakes were Richter magnitude (surface wave) 5–6 and two were magnitude 4–5 (fig. 10); the rest were less than magnitude 4. Of the two largest earthquakes, one was located near Lake Mead and may have been related to its filling; the other was near the lower Gila River. Two additional large earthquakes, magnitude 5–6 and 6–7, which occurred north of Imperial Reservoir just outside the region to the west, affected the region as shown by the strain-release lines. Areas showing the greatest strain release are in the southwestern part of the region, where the two large earthquakes north of Imperial Reservoir occurred and in the northwestern part of the region near Lake Mead.

A similar compilation of earthquake data has been made for Arizona by DuBois and others (1982). Within the Sonoran region they reported 11 instrumentally recorded and five historically recorded epicenters of Richter magnitude less than 5.0 between 1830 and 1980. Menges and Pearthree (1983, fig. 5) suggested a correlation between historical seismicity and late Pliocene and Pleistocene faulting within a 200-km-wide zone that extends from the western Colorado Plateau diagonally southeastward into southwestern New Mexico. Menges and Pearthree also indicated a 60-km-wide zone of historical seismicity (11 recorded epicenters) in the southernmost Sonoran region. This zone, which trends west-northwest through the Yuma area, parallel to the Mexican border, has only minimal prehistoric surface-rupture expression. The Algodones fault with obvious surface rupture lies in this zone near the Mexican border 35 km southeast of Yuma. Menges and Pearthree's 60-km-wide seismicity zone may merge to the west with the San Andreas fault system in California, even though the two trends are divergent by 30°.

[3]Arizona Bureau of Geology and Mineral Technology.

HEAT FLOW

About 40 heat-flow measurements have been reported for the Sonoran region of Arizona (J.H. Sass, U.S. Geological Survey, written commun., 1982). Of these measurements, only two exceed 2.5 heat-flow units (HFU) (fig. 10), and the maximum measurement is 2.82 HFU. The entire Sonoran region of Arizona has a heat flow ranging from 1.5 to 2.5 HFU (J.H. Sass, written commun., 1982).

QUATERNARY FAULTING

Mapped Quaternary faults are exceedingly few in the Sonoran region of Arizona (Nakata and others, 1982; Menges and Pearthree, 1983). In addition to those faults mentioned in the previous section on seismicity, a few short segments occur around the periphery of the region; none have been mapped in the interior (fig. 10). Quaternary faults that have been studied show displacements older than 10,000 yr.

LATE CENOZOIC VOLCANICS

The Sentinel Plain–Arlington volcanic field occurs north and south of the Gila River near Gila Bend. Only the Sentinel Plain part of the field is in the region (fig. 10). It contains fine-grained olivine basalt flows and cinder cones, which have late Cenozoic dates ranging from 1.72 to 3.19 m.y. (Aldrich and Laughlin, 1981; Eberly and Stanley, 1978; Shafiqullah and others, 1980). Based on weathering characteristics of the flows and the K/Ar dates, only a small part of the Sentinel Plain field is believed to be Quaternary in age (R.B. Scarborough, Arizona Bureau of Geology, unpublished data, 1984). Most of the Quaternary radiometric dates come from the Arlington and Gillespie cones farther to the northeast.

Aldrich and Laughlin (1981) show basalt no older than 3 m.y. cropping out north of Imperial Reservoir in the southwestern part of the region. Garner and others (1982) suggested that the flow, shown on the State geologic map as Quaternary basalt (Wilson and others, 1969), is actually late Miocene or Pliocene in age.

VERTICAL CRUSTAL MOVEMENT

Gable and Hatton (1983) show an area of uplift in southern California and southwestern Arizona. Based on geodetic leveling, the southwestern Sonoran region of

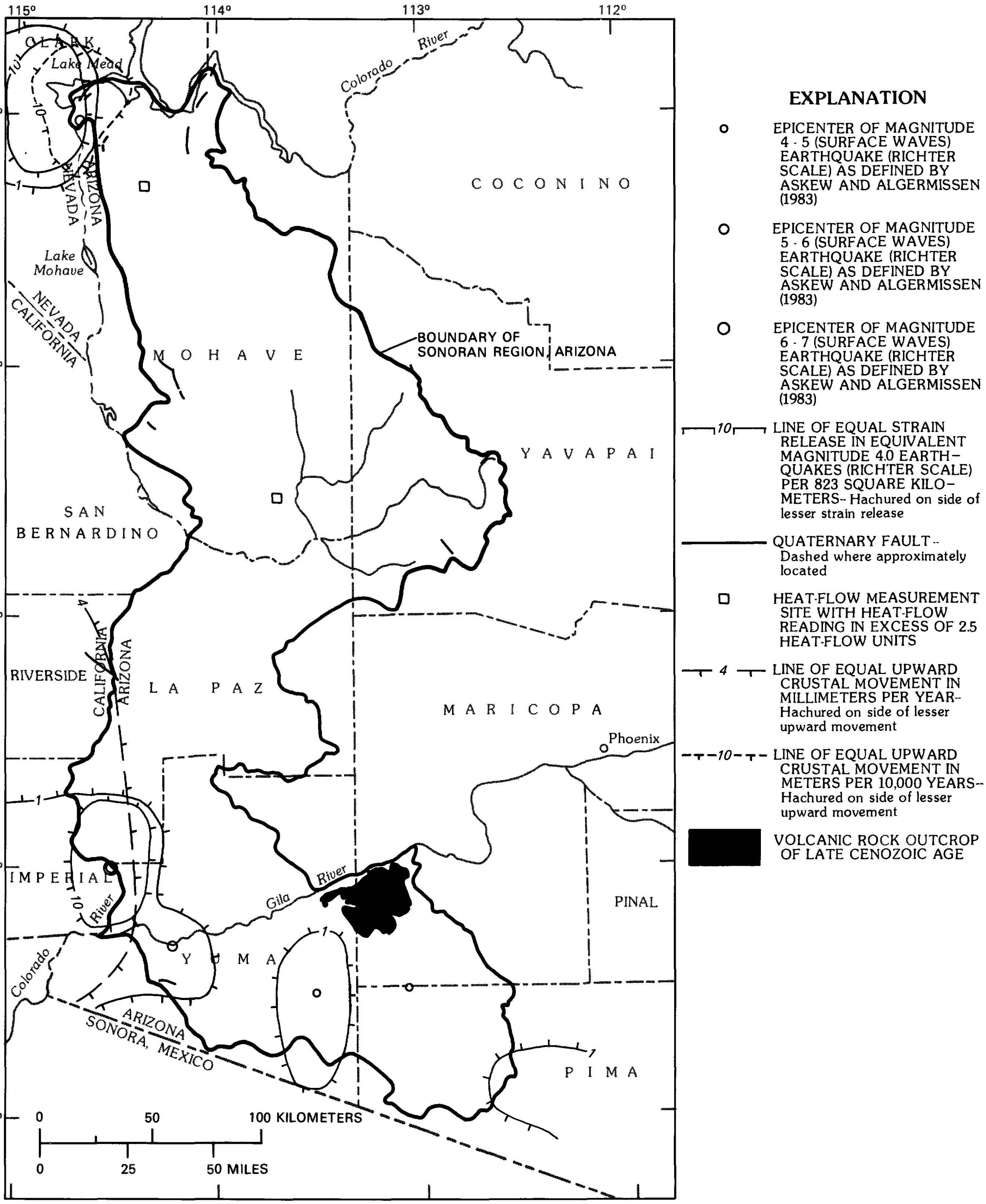

FIGURE 10.—Seismicity, heat flow, Quaternary faults, late Cenozoic volcanic rocks, and vertical crustal movement.

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

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GROUND–WATER HYDROLOGY

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

The Sonoran region of Arizona is arid for the most part, with mean annual precipitation less than 200 mm throughout most of the region and potential evaporation greater than 2.5 m. Annual precipitation is greatest in ground-water unit SA–07 where it reaches a maximum of about 500 mm. Surface drainage of the structural basins is open, except for part of the Hualapai basin (ground-water unit SA–09).

MAJOR HYDROGEOLOGIC UNITS

The hydrogeologic units in the region include basin fill, volcanic rocks, clastic indurated sedimentary rocks, carbonate rocks, and crystalline rocks, including intrusive and metamorphic rocks (pl.3).

Basin fill (including alluvial material of stream valleys) occurs largely in structural basins and is as thick as 3,000 m. The basin fill crops out at the land surface throughout a large part of the region; however, pediment surfaces underlie the fill at shallow depths beneath one-half to two-thirds of the basin-fill area.

The basin fill consists mostly of nonindurated to semi-indurated sedimentary terrestrial and marine deposits. The ages of the deposits range from middle Tertiary to Holocene. The terrestrial deposits consist largely of poorly sorted to moderately sorted mixtures of gravel, sand, silt, and clay that were derived largely from the consolidated rocks in the nearby mountains. The fill also contains volcanic flows and ash falls from episodic volcanic activity during the Tertiary and Quaternary Periods. Fine-grained lake deposits, silt and clay, and evaporitic deposits of salt, gypsum, and limestone, have been found in many of the basins. The stratigraphic sequence of basin-fill deposits in the Ranegras Plain, the Wellton-Mohawk area, and the Gila Bend basin have been described from drill cuttings by Metzger (1952a, b). The basin fill in most basins has not been fully penetrated by wells and the lithology is areally variable. However, the lithologic sequence described may be similar to sequences in other basins. The older fill is described as semi-indurated fine-grained deposits, identified as lake-bed deposits in some areas, with minor interbedded sand, and ranges in thickness from 60 to 240 m. Overlying the fine-grained material is a coarser unit composed of sand and gravel described as being about 100 m thick. A thickness of more than 300 m of salt, and interbedded fine-grained material, presumably of lake deposition, has been reported near Red Lake in the Hualapai Valley (Gillespie and others, 1966).

Marine estuarine deposits in Tertiary (Miocene and Pliocene) extensions of the Gulf of California have been described in the Yuma area (Olmsted and others, 1973) and in the Parker-Blythe-Cibola area (Metzger and others, 1973). The marine deposits predominantly are thin-bedded silt and clay with some calcareous material, and may be as thick as 600 m in the Yuma area. Marine deposits are present in other basins in the region but their facies have not been positively identified. Metzger (1952a) noted a fine-grained sequence in the Gila River valley, possibly equivalent to the marine deposits of the Yuma area. The maximum thickness of fill in individual basins ranges from about 250 to 3,000 m with most basins having a maximum thickness of 1,000–2,000 m (Oppenheimer and Sumner, 1980).

Volcanic rocks are grouped hydrologically as undifferentiated volcanic rocks, which include flows and pyroclastic materials of Mesozoic and Tertiary age and tuff of Tertiary age. Volcanic rocks overlie older consolidated rocks and locally compose part of the basin filling. Coarse-clastic sedimentary rocks of Mesozoic age are as thick as 4,000 m locally, and are scattered throughout the region. Carbonate rocks of Paleozoic age occur in a limited area in the northern part of the region.

Crystalline rocks are widespread and underlie the entire region at depth. The rocks in this hydrogeologic unit include metamorphic rocks and intrusive-igneous rocks and range in age from Precambrian to Tertiary.

GROUND–WATER FLOW REGIME

Ground-water recharge occurs by infiltration of precipitation. The greatest opportunity for recharge is in areas of permeable surface rock during periods when precipitation is in excess of evapotranspiration. Lacking direct evidence of the location and timing of recharge, it generally is assumed that much of the recharge occurs near the mountain fronts during surface runoff to basin-fill deposits. Some recharge occurs within the mountain ranges, but the minimal permeability of the rocks and steep slopes promote rapid runoff of rainfall and snowmelt. The basin fill, being more permeable, is more receptive to infiltration of runoff from the mountain ranges. The central parts of the basins receive some recharge, but probably minor quantities because of generally minimal precipitation and substantial potential evapotranspiration. Recharge to the central parts of the basin fill may largely occur at infrequent times during rare storm runoff.

Discharge of ground water occurs by seepage to gaining streams, by evapotranspiration, by withdrawal from wells, and from springs. Gaining streams include reaches of the Colorado River, the Gila River, and the Bill Williams River and its tributaries. Ground-water unit SA–07 contains not only numerous gaining stream reaches of the Bill Williams River and its tributaries, but also a dozen or more noteworthy springs.

Springs having discharge temperatures of 31 °C or greater, and discharges of 200 L/min or greater are shown in plate 4. The largest concentration of springs is in ground-water unit SA–07. These include two springs in the Big Sandy River drainage having temperatures of 37 °C. Two springs with temperatures less than 30 °C and known discharges of greater than 200 L/min also occur in ground-water unit SA–07.

Radium Hot Spring in the Gila River valley was reported as dry by Berry and others (1980). At one time the spring had been developed as a health resort and had a temperature of 60 °C. The original flow was small and has ceased, possibly because of ground-water withdrawal by wells in the vicinity.

Four springs with temperatures less than 30 °C and flowing greater than 200 L/min are known to occur in the region outside ground-water unit SA–07. Two are in the eastern arm of ground-water unit SA–09 and two are in ground-water unit SA–08.

Ground water is withdrawn through wells, largely for irrigation, in localized areas scattered throughout the region. The greatest withdrawals are along the Gila and Colorado Rivers and in the Sacramento Valley, Ranegras Plain, Butler Valley, and Hualapai Valley.

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 at the water table are shown in plate 3. Relative velocities are reported because site-specific data were not available for the region. Hydraulic properties of the hydrogeologic units were estimated using values in Chapter A and modified from the lithologic and hydrologic description of the units in the literature, and further modified as appropriate during verification of the cross-sectional models (Bedinger, Langer, and Reed, 1989). The values of hydraulic properties of the units and hydraulic gradients used in estimating relative ground-water velocities are given in table 1.

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. 3)	K/ϕ (meters per day)	Hydraulic gradient
Basin fill	a	6×10^{1}	0.003
Carbonate rocks	c	1×10^{1}	.003
Coarse clastic rocks	s	2×10^{-1}	.03
Granitic rocks	g	2×10^{-1}	.03
Metamorphic rocks	m	2×10^{-1}	.03
Volcanic rocks			
Undifferentiated	v	1×10^{-1}	.03
Lava flows	b	3×10^{0}	.03
Ash-flow tuff	t	1×10^{-1}	.03

The hydraulic gradients for the hydrogeologic units are representative gradients obtained from the water-level contour map of the region (Langer and others, 1984). Relative ground-water traveltimes are shown in plate 4. Flow paths along which the relative ground-water traveltimes were calculated and major discharge areas also are shown in plate 4. Traveltimes are computed from ground-water divides to the gaining reaches of streams and major pumping centers.

The longest relative traveltimes, 10 to 20, occur from a few small areas of undifferentiated volcanic rocks and intrusive and metamorphic rocks near ground-water divides to discharge areas. Generally, the relative flow time from points in basin fill to discharge areas is less than 1.

The relative traveltimes indicated in the map from divide areas to discharge areas are extremely conservative because actual flow paths in recharge areas dip below the water table and therefore, both the actual flow path and actual 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 following discussion of cross-sectional models.

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

TABLE 2.—*Hydraulic properties of hydrogeologic units modeled in hydrogeologic sections*

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

Rock type	Symbol (pl. 5)	Hydrogeologic sections on plate 5					
		A–A'		*B–B'*		*C–C'*	
		K	ϕ	K	ϕ	K	ϕ
Ash-flow tuff	t	4×10^{-4}	3.5×10^{-1}	---	---	---	---
Crystalline rock, upper part of section	G	5×10^{-4}	3×10^{-3}	5×10^{-4}	3×10^{-3}	5×10^{-4}	3×10^{-3}
Crystalline rock, lower part of section	g	3×10^{-7}	1×10^{-4}	3×10^{-7}	1×10^{-4}	3×10^{-7}	1×10^{-4}
Undifferentiated volcanic rocks	v	4×10^{-4}	4×10^{-3}	4×10^{-4}	4×10^{-3}	4×10^{-4}	4×10^{-3}
Coarse-grained basin fill, upper part of section	a	5×10^{0}	1.8×10^{-1}	5×10^{0}	1.8×10^{-1}	1×10^{-1}	1.8×10^{-1}
Coarse-grained basin fill, lower part of section	B	1×10^{-1}	1.2×10^{-1}	1×10^{-1}	1.2×10^{-1}	1×1^{-1}	1.2×10^{-1}
Fine-grained basin fill	A	---	---	2×10^{-4}	3.2×10^{-1}	---	---

Chapter A of this report (Reed, 1989). The map location of the sections and the model parameters and results are shown in plate 5. The values of hydraulic properties of the rock units in the hydrogeologic sections used in analysis of the ground-water flow are given in table 2.

Distribution of rock units, relative traveltimes, and stream functions are given in plate 5. 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 flow line to the discharge area. Stream functions show the directions of ground-water movement and relative quantity of flow in the section below the flow line.

The sections give a more realistic concept than plate 4 of the traveltime between widely spaced points in the region, for example, between the water-table divide areas and the discharge areas. As shown in plate 5, the flow paths in the divide areas of the flow system dip steeply into the flow system and take the longest flow paths to the discharge areas. Relative traveltimes from the divide areas to discharge areas are as great as 10^6 to 10^8. Commonly, these longest relative traveltimes are of restricted surface area at the water table. The areas of longer relative traveltime enlarge with depth. One would be more confident in locating an area of long traveltime at depth beneath the water table than near or above the water table where the area of long traveltime is small.

Broad areas of relative traveltime of 10^5 or greater exist at the water table in all sections and areas of traveltime 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, Arizona, is characterized by the areal distribution of dissolved solids (fig. 11) and predominant chemical constituents in solution (fig. 12). These maps are generalized from those compiled by Thompson and others (1984). The maps of Thompson and others (1984) were compiled from data in the water-quality files of the U.S. Geological Survey (WATSTORE) and in published reports. The data are mostly from nongeothermal springs and wells less than 150 m deep completed in alluvial and basin-fill deposits. In areas where data were not available, the water-quality characteristics were

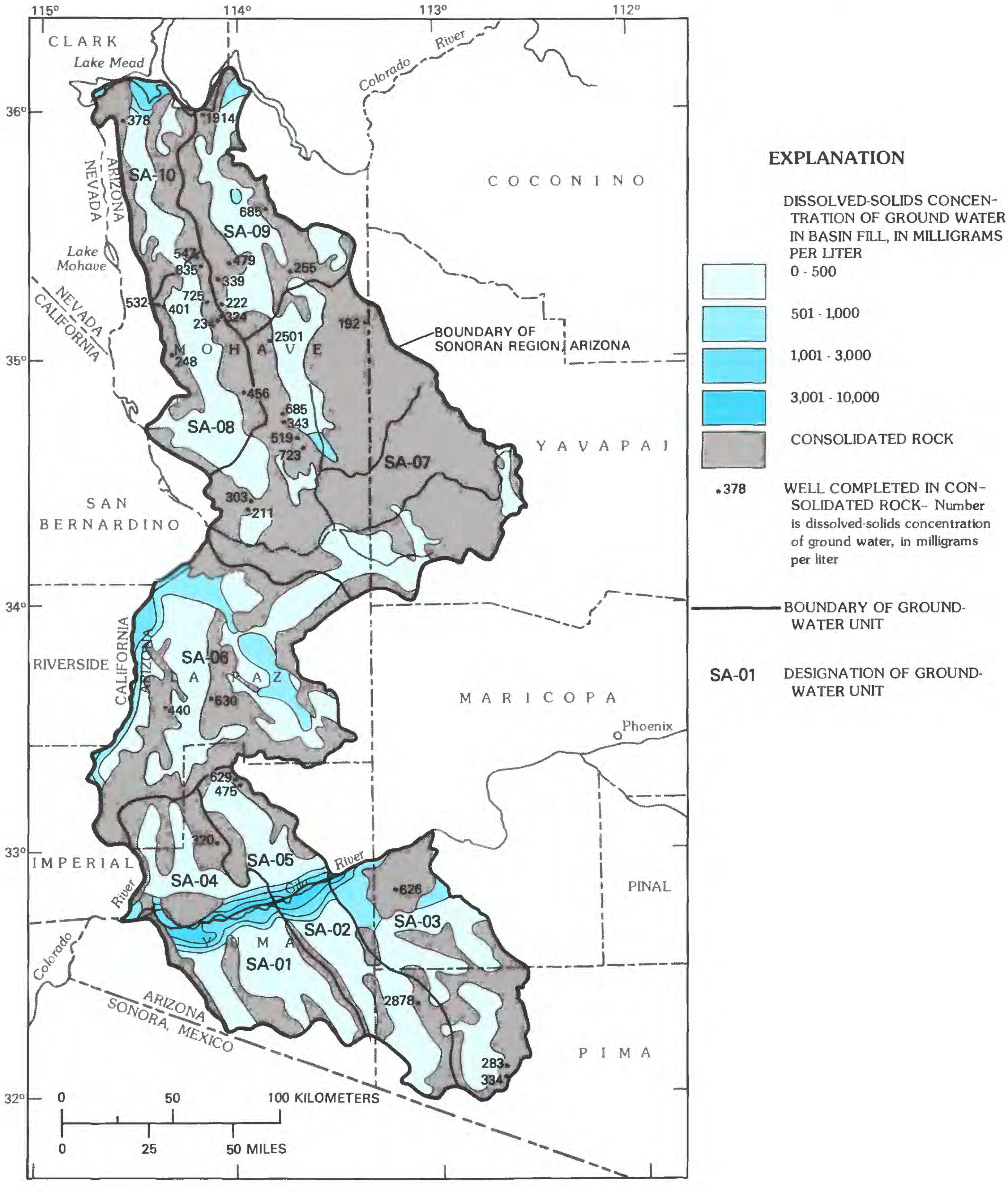

FIGURE 11.—Dissolved-solids concentration in ground water.

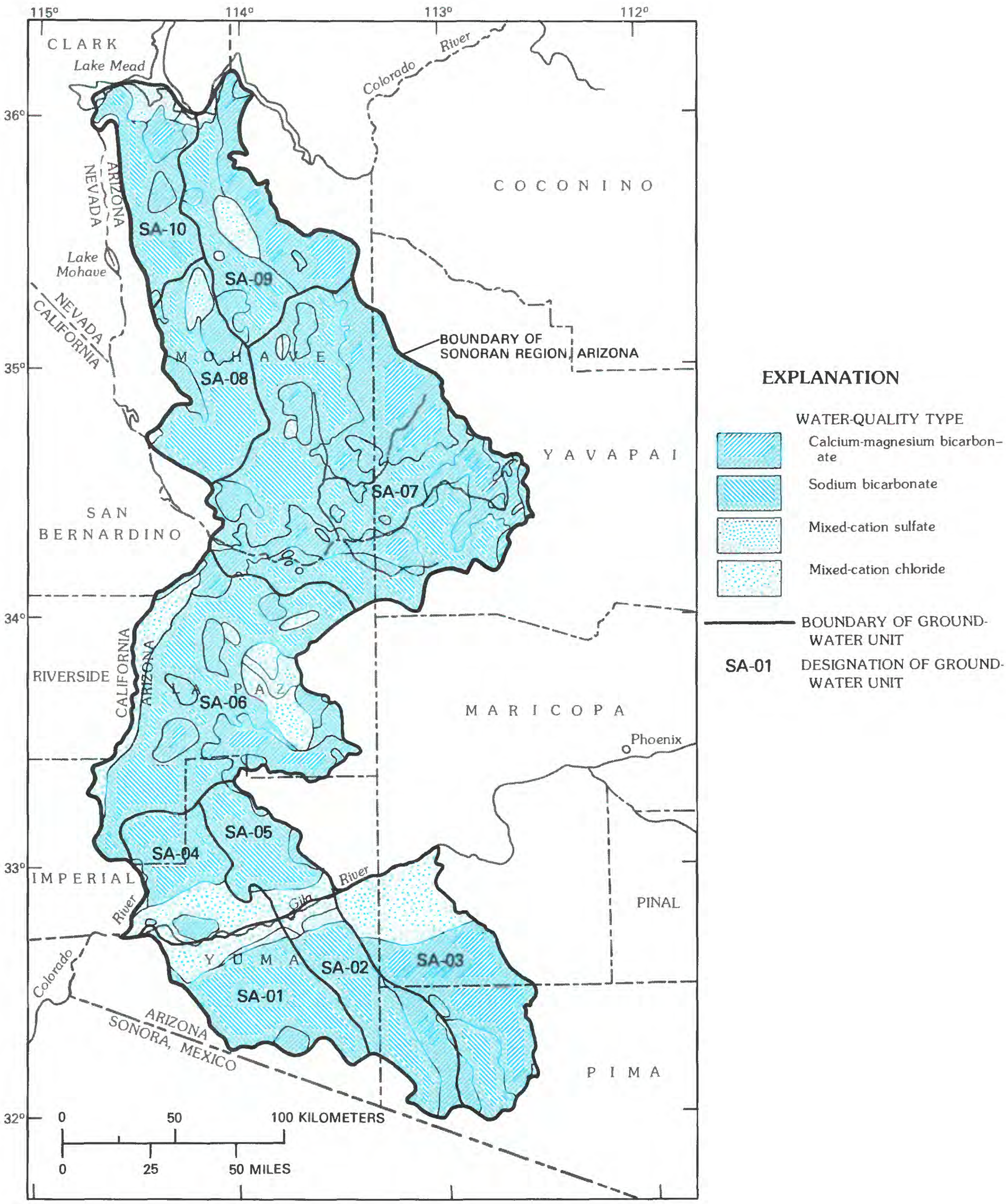

FIGURE 12.—Distribution of chemical types of ground water.

estimated from the position in the ground-water flow system and the lithology of the local bedrock.

In most of the region, the concentration of dissolved solids in ground water is less than 500 mg/L. Ground water near the Gila River contains 3,000–5,000 mg/L dissolved solids with concentrations as great as 15,000 mg/L. The dissolved-solids concentration near Lake Mead and the Colorado River is between 1,000 and 3,000 mg/L. Concentrations of dissolved solids are between 500 and 1,000 mg/L in a large part of the Ranegras Plain. The ground water is mostly of the calcium magnesium or sodium bicarbonate type. Waters in which the dominant anion is sulfate or chloride occur in and near large discharge areas and in some playas.

PLEISTOCENE HYDROLOGIC CONDITIONS

There is no evidence of Pleistocene lakes in the Sonoran region of Arizona, and the drainage in the Pleistocene Epoch is presumed to have been integrated as it is today, except for the closed basin occupied by the dry Red Lake. During glacial maxima, sea level may have been as much as 80–140 m lower (Bloom, 1978, p. 406), and entrenchment of the Colorado and Gila Rivers may have resulted in a lower base level for ground-water discharge. Glacial climate was probably characterized by increased precipitation and decreased temperature and evaporation as inferred from maximum Pleistocene lake levels in the Basin and Range province (Leopold, 1951; Reeves, 1966; Snyder and Langbein, 1962) and from plant macrofossils (Spaulding, 1983). The dry Red Lake bed occupies part of a closed basin in ground-water unit SA–09 but contains no reported evidence of having been occupied by a lake during the Pleistocene. Peirce (1976) believes that the basin was occupied by a closed-basin lake during the Miocene during which time several hundred meters of evaporites with interbedded silt and clay accumulated. If the closed basin existed in the Pleistocene, as it probably did, the precipitation in the basin was lost by evaporation and infiltration to the subsurface and discharge as ground water to the Colorado River to the north. The entrenchment of the Colorado River, probably in the Pliocene (subsequent to 5.9 m.y. ago, Shafiqullah and others, 1980), and consequent development of a base level for ground-water discharge 625 m below the surface of the playa may have prevented the basin from developing a lake during the Pleistocene.

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MINERAL AND ENERGY RESOURCES

By B.T. BRADY and ROBERT B. SCARBOROUGH[4]

The Sonoran region of Arizona contains mineral deposits which occur in diverse geologic environments and are of several ages. Historically, base- and precious-metal ores have been the principal sources of metals in the region. Of these commodities copper, molybdenum, silver, and gold are currently the most important to the State's mineral economy. Early mineral development in the Sonoran region of Arizona was confined to precious-metal lodes, base-metal vein and replacement ores, and placer deposits. These deposits with few exceptions were extensively developed by the close of the 19th century. More recent development has been focused on large scale open-pit copper mines which produce substantial quantities of precious metals as coproducts or byproducts.

METALLIC MINERAL RESOURCES

The mineralized areas discussed in this report have been delineated by Keith, Gest, and DeWitt (1983) and Keith, Schnabel, DeWitt, Gest, and Wilt (1983). These areas are characterized as unique metallogenic systems, which have been defined on the basis of mineralization age and style. These areas generally comprise areas of identified resources with documented production but do not contain every known ore mineral occurrence. This report is not meant to contain an assessment of areas of mineral potential. Commodities of primary importance in the mineralized areas are metallic minerals that contain any of the following elements: copper, lead, zinc, molybdenum, iron, manganese, barium, gold, silver, mercury, platinum, lithium, beryllium, tin, tungsten, and uranium.

The Sonoran region of Arizona contains more than 115 metallic mineral districts (Keith, Gest, and DeWitt, 1983; Keith, Schnabel, DeWitt, Gest, and Wilt, 1983), which have individually and collectively contributed substantially to the total State nonfuel mineral production. Boundaries of these metallic mineral districts (pl. 6) represent the general extent of known productive workings and prospects and do not indicate limits of mineralized rock. These predominantly base- and precious-metal ores have been mined from deposits of various forms and ages. The principal production to date has been from disseminated and stockwork porphyry deposits, vein and replacement deposits, and, to a lesser extent, from stratabound deposits. The principal base- and precious-metal production for the metallic mineral districts, which have produced more than 90,780 Mg (metric ton) of ore, are summarized in table 3.

Copper has been noted in the majority of the mineralized areas within the Sonoran region of Arizona (Anderson, 1969; Keith, Gest, and DeWitt, 1983; Keith, Schnabel, DeWitt, Gest, and Wilt, 1983), and the principal sources of this metal in the study area are the mines in the Eureka, Ajo, and Wallapai mining districts. Eighteen of the Nation's 25 leading copper-producing districts are located in Arizona. During 1981 the Eureka, Ajo, and Wallapai districts ranked 9th, 17th, and 23d, respectively, in total domestic copper production (Butterman, 1983).

Production of copper from the disseminated and stockwork deposits in the Eureka (Bagdad) district during 1981 was 64,869 Mg (Burgin, 1983), and large quantities of molybdenum and gold are recovered annually as byproducts. Base- and precious-metal veins and massive replacement deposits also have been important metal sources in the district. Mineralization at Eureka was related to the intrusion of a Laramide quartz-monzonite stock. The geologic history and character of the mineral deposits of the Eureka district are complex and have been described in detail by Butler (1938), Anderson (1948; 1950a, b), and Anderson and others (1955).

The New Cornelia disseminated porphyry-copper orebody in the Ajo district occurs in the brecciated Laramide Cornelia quartz monzonite and, to a lesser extent, in the surrounding quartz-diorite facies and Cretaceous(?) Concentrator volcanics. Copper, substantial quantities of byproduct silver and gold, and lesser quantities of molybdenum constitute the primary metals produced since the inception of large-scale mining about 1917. The cumulative base- and precious-metal production from the New Cornelia open-pit mine exceeded $1.5 billion by 1972 (Keith, 1974). Discussions of the geology and mineral deposits near Ajo are contained in articles by Joralemon (1914), Bryan (1925), Ingham and Barr (1932), Gilluly (1937, 1938, 1942, 1946, 1952), and Dixon (1966).

The Wallapai mining district is located in the north-trending Cerbat Mountains in northern Mohave County. Isoclinally folded schist, gneiss, and amphibolite of the Precambrian Cerbat complex are locally intruded by Precambrian granite and a compositionally and texturally zoned Laramide quartz-monzonite stock. Mineralization in the district is of multiple ages and types. An early stage of stockwork-copper deposits formed mainly within predominantly northwest-trending fractures in the brecciated Mesozoic(?) Ithaca Peak Granite (Eidel and others, 1968). Northwest-trending,

[4]Arizona Bureau of Geology and Mineral Technology.

TABLE 3.—*Production summary of base and precious metals for metallic mineral districts, by county*

[Total production in excess of 100,000 short tons (including estimates for years data not available). Commodities listed in other commodity column: Mn, manganese; Mo, molybdenum; U_3O_8, yellow cake; V_2O_5, vanadium pentoxide; and W, tungsten. Data from Keith, Gest, DeWitt, and others (1983) unless otherwise noted]

County	Metallic mineral district	Production period	Ore (thousands of short tons)	Copper (thousands of pounds)	Lead (thousands of pounds)	Zinc (thousands of pounds)	Gold (ounces)	Silver (hundreds of ounces)	Other commodity (thousands of pounds unless noted)
LaPaz County									
	Little Harquahala.	1888–1963	159	50	156	---	143,000	900	---
	Silver	1880–1951	103	2	2,456	---	<100	13,110	---
Mohave County									
	Artillery Peak.	1946–1959	---	---	---	---	---	---	[1]95,108(Mn)
	Boriana	1919–1957	239	408	---	---	100	125	[2] >121,324(W)
	Emerald Isle	1917–1973	1,418	22,166	---	---	<100	4	---
	Hualapai	1918–1970	161	7,247	897	11,370	700	990	---
	McCracken	1911–1981	173	10	3,031	43	100	6,990	[3]100(Mo)
	Oatman	1870–1980	4,073	60	---	---	1,966,000	11,470	---
	Pilgrim	1929–1945	281	---	---	---	48,000	720	---
	Planet	1862–1970	1,010	19,520	---	---	400	3	---
	Swansea	1909–1962	545	26,457	---	---	500	330	---
	Union Pass	1868–1943	704	---	---	---	128,000	3,130	---
	Wallapai	1909–1981	96,920	666,137	80,096	126,487	151,000	115,350	53,180(Mo)
Pima County									
	Ajo	1899–1979	430,038	6,026,380	30	---	1,558,000	196,720	450(Mo)
Yavapai County									
	Copper Basin	1901–1968	357	19,631	508	1,400	500	457	---
	Eureka (includes 1880 estimate from Hillside mine).	1890–1981	101,417	1,306,111	7,866	3,624	67,000	46,910	16,535(Mo) 46(Mn) [3]116(U_3O_8) [3]13(V_2O_5)
	Martinez (Congress mine).	1887–1950	990	201	2	---	432,500	4,660	---
	Old Dick	1917–1977	1,683	106,396	3,041	306,584	3,500	6,520	---
	Rich Hill	1895–1970	745	124	882	---	203,000	1,890	---
Yuma County									
	Castle Dome	1870–1900	4	---	7,350	---	---	2,480	---
		1884–1990	---	---	---	---	3,617	---	---
		1901–1981	120	53	11,582	29	3,000	2,540	---
	Kofa	1897–1957	675	7	2	---	237,000	1,070	---

[1]Area extends southward into La Paz County.

[2]Production in short-ton units. A short-ton unit of WO_3 is 1 percent of a short ton or 20 pounds of WO_3, and contains 15.8614 pounds of tungsten metal.

[3]Production in pounds.

lead-zinc vein deposits overlie and are peripheral to the porphyry-copper deposits (Thomas, 1949). Tertiary supergene turquoise deposits that occur superimposed above the stockwork deposits and Quaternary supergene(?) chrysocolla deposits that formed at Emerald Isle are the results of late-stage oxidation and mineralization in the Wallapai district. Initially the principal production was from vein deposits, whereas more recent development has been confined to the porphyry-copper deposits. The cumulative total ore production from the Wallapai district through 1981 has been estimated to exceed 87,148 Mg (Keith, Gest, DeWitt, Toll, and Everson, 1983).

Eleven of the 46 mineral districts in Arizona that have produced more than 10,000 oz of gold occur within the Sonoran region of Arizona study area. These include the Ajo, Cienega, Eureka, Kofa, Little Harquahala, Martinez, Oatman, Pilgrim, Rich Hill, Union Pass, and Wallapai districts. Collectively they have produced nearly 5 million oz of gold (Koschman and Bergendahl, 1968; Keith, Gest, Dewitt, Toll, and Everson, 1983). The majority of the gold produced in Arizona prior to 1900 came from lode deposits of various mineralization ages and styles, and placer deposits, whereas the majority of the State's gold mined during the 20th century has been produced as a byproduct of large-scale, low-grade copper mining. Arizona ranked fourth among the Nation's leading gold producers during 1981 (Lucas, 1982).

Lead and zinc minerals occur primarily in vein and replacement deposits in the Sonoran region of Arizona. Lead minerals commonly contain substantial quantities of silver, and historically lead-bearing ores have been mined as a source of silver. The most significant production of lead has come from deposits in the Wallapai district, Mohave County, and in the Eureka area, Yavapai County. Smaller, although locally important, tonnages of lead were mined from vein deposits in the Castle Dome district, Yuma County, and in the McCracken district, Mohave County. The McCracken district deposits were reworked substantially in 1981 (Keith, Gest, DeWitt, Toll, and Everson, 1983). More than one-half of the lead produced in Arizona during 1981 came from large copper mines (Burgin, 1983). The McCracken district and Mineral Park area in the Wallapai district ranked first and sixth, respectively, in Arizona lead output during 1981.

The Old Dick and Copper Basin districts in Yavapai County and the Wallapai and Hualapai districts in Mohave County have been the principal sources of zinc in the Arizona Sonoran region. Zinc was recovered at the Mineral Park area in the Wallapai district and from a few base- and precious-metal mines in the study area during 1981 (Burgin, 1983).

Silver and molybdenum have been recovered in significant quantities as byproducts of open-pit copper mining at the Mineral Park area in the Wallapai district and in the Eureka district. The New Cornelia mine in the Ajo district also has produced substantial silver and small quantities of molybdenum. Furthermore, silver has been mined from important precious-metal lode and placer deposits and from base-metal fissure veins in the study area. The most notable of these areas, which have produced more than 500,000 oz of silver, include the Silver, Oatman, McCracken, Old Dick, Hackberry, and Castle Dome districts. Arizona mines accounted for 20 percent of the Nation's 1981 silver production and 30 percent of the Nation's total molybdenum output (Burgin, 1983).

A large, domestically important manganese resource occurs in the Artillery Peak district. This syngenetic deposit occurs in the upper few hundred meters of clastic sediments in the Miocene Chapin Wash Formation. Two horizons of mineralization have been noted, and the upper zone has been the principal development target to date. An estimated 337,702 Mg of ore were mined from the shallow manganese-bearing horizon for government stockpiles during 1951–56 (Farnham and Stewart, 1958). This area contains more than 159 million Mg of manganese ore that averages 3.5–4 percent manganese (Lasky and Webber, 1949). A smaller deposit of manganese oxide similar to the syngenetic ores in the Artillery Mountains occurs at the Doyle mine in the Alamo district. Several million pounds of manganese also have been produced from deposits in the Lincoln Ranch and Bouse districts in La Paz County and in the Trigo Mountains district in Yuma County (Keith, Gest, DeWitt, Toll, and Everson, 1983). Numerous other scattered occurrences of manganese occur in western Arizona as epigenetic fissure fillings and irregular replacement deposits. These deposits commonly are of low grade and usually are associated with base metals, which decrease the commericial value of the ore.

Tungsten has been mined from deposits in 10 metallic mineral districts in the Sonoran region of Arizona (Wilson, 1941b). Although tungsten occurs in several modes, irregular vein and replacement deposits in silicic plutonic and metamorphic rocks are the principal sources of this metal in Arizona. Wolframite- and scheelite-bearing quartz veins in the Boriana district have yielded more than 133,735 Mg of tungsten (Keith, Gest, DeWitt, Toll and Everson, 1983). A few thousand metric tons of tungsten were mined in the Tungstona, Wheeler Wash, and Aquarius Mountains districts, and smaller tonnages were produced from mines in the Ellsworth, Kofa, Fluorescent, Zannaropolis, Ophir, and Lost districts.

A few hundred flasks of mercury were produced from a narrow, brecciated quartz vein in the La Cholla district in the Dome Rock Mountains prior to 1914 (Lausen and Gardner, 1927; Wilson, 1941a; Bailey, 1969).

Within the region, three areas have been intensively explored and drilled for uranium. The Date Creek basin contains reserves of 18 million pounds of UO in a Miocene carbonaceous lacustrine sequence within 200 m of the surface (Sherborne and others, 1979), and very large potential resources exist in deeper parts of the basin (Otton, 1981; May and others, 1982). Sediments of similar age in the Big Sandy River valley 10–30 km north of Wikieup contain several low-grade uraniferous zones buried beneath shallow less deformed gravels throughout an area of several square kilometers (Scarborough, 1981). Numerous vein and fissure uranium occurrences, some with thorium, are known in the Cerbat Mountains north of Kingman and are related to base- and precious-metal mineralization in that area (Scarborough, 1981). Of these three areas, minor uranium production has been recorded only from the Date Creek basin. Although many other metallic minerals have been reported to occur sporadically in the mineralized areas of the Sonoran region of Arizona, they are chiefly of mineralogical importance and will not be discussed here.

NONMETALLIC AND INDUSTRIAL MINERAL RESOURCES

Nonmetallic and industrial minerals are of widespread occurrence in the Sonoran region of Arizona; however, these materials have been produced only intermittently, primarily for local use. More than 28 varieties of nonmetallic and industrial minerals and rocks are reported to occur within the study area. The distribution and nature of these minerals and rocks have been shown or described in publications by Wilson and Roseveare (1949), McCrory and O'Haire (1961), U.S. Geological Survey, Arizona Bureau of Mines, and U.S. Bureau of Reclamation (1969), and Elevatorski (1975). The occurrences of semiprecious or precious gemstones, ornamental and building stone, and natural aggregates will not be described in this report. The nonmetallic mineral commodities, which have generally small production, include barite, fluorspar, bentonite, kaolinite, feldspar, mica, gypsum, halite, brucite, and magnesite.

Approximately 2,723 Mg of barite worth nearly $27,000 were produced collectively from veins in faulted Precambrian granite, schist, and gneiss, and, to a lesser extent, from fissure fillings in Tertiary volcanic rocks in the Harcuvar, Plomosa Pass, and Mohawk districts (Keith, 1978). Small quantities of barite also have been mined from deposits north of the Bouse and Three-In-One districts in Mohave County (Elevatorski, 1975). Barite also occurs as a common gangue mineral in many of the vein and replacement deposits in the Sonoran region of Arizona.

Argentiferous galena-fluorite veins in the Castle Dome district yielded nearly 2,723 Mg of metallurgical-grade fluorspar during 1902–17 and in 1953 (Wilson, 1950; Van Alstine and Moore, 1969). These veins comprise north- to northwest-trending fissure filling deposits that crosscut Mesozoic shales and diorite and rhyolite porphyry dikes (Wilson, 1933). Fluorite localities are common in the study area. The mineral usually is associated with barite, calcite or quartz, manganese oxides, and, to a lesser extent, with beryllium, tungsten, and uranium minerals in several precious- and base-metal vein deposits.

A few hundred megagrams of bentonite were mined for drilling mud near Bouse (Wilson and Roseveare, 1949), and small quantities of lithium-bearing montmorillonite have been produced for a sealer from the Lyles clay deposit 14.5 km northwest of Kirkland (Norton, 1965). An estimated 1 million Mg of bentonite was reported to occur within the smectite deposit along Burro Creek 12.8 km west of Bagdad (Funnell and Wolfe, 1964). The majority of these deposits of bentonite probably formed by alteration of Cenozoic volcanic ash or of tuffaceous or lacustrine sediments; however, the genesis of these occurrences has not been fully documented. Kaolinite associated with quartz and cristobalite occurs in altered volcanic rocks at the Klaner and Doolin prospect near the southwestern end of Black Mesa, Mohave County (Elevatorski, 1975). Although kaolinite has been intermittently mined as a refractory material from a few small deposits, no production data are currently available.

Pegmatites at several localities in the region have been mined sporadically to acquire materials for abrasives, ceramics, glass, enamels, drilling mud, and local smelter flux (Elevatorski, 1975).

Gypsum has been extracted for agricultural use from small deposits in Permian limestone at the Blue Moon and Townsend properties near Bouse (Elevatorski, 1975).

The principal occurrences of halite in the Arizona Sonoran region are located in the Hualapai and Detrital Valleys in central Mohave County. The Detrital Valley bedded-salt deposit attains a maximum thickness of 218 m and is associated with gypsum- and anhydrite-bearing clastic sediments of the Miocene Muddy Creek Formation (Peirce, 1981b). The massive body of halite at Red Lake in the Hualapai Valley is more than 1,000 m thick. Southwest Gas Co. currently plans to utilize the Red Lake salt deposit for storage of natural gas (Peirce, 1981a). Subsidence due to solution of salt has not been recognized to date in the vicinity of either salt body.

A potential brucite resource in the Tertiary volcanic rocks in the Oatman district reportedly contains more than 9,078 Mg of low-grade magnesium oxide (Gildersleeve, 1962; Ericksen, 1969). The brucite-bearing horizons, which contain abundant calcite, dolomite, and lesser quantities of magnesite and hydromagnesite, are parallel to the enclosing volcanic rocks and locally attain a maximum composite thickness of 9 m. Although a small quantity of brucite was mined in 1953, the low grade of the material prevented sustained shipments.

Nonmetallic and industrial minerals and rocks occur throughout the region. These commodities have been developed primarily for local markets, however, and there has been no sustained production of any of these commodities.

GEOTHERMAL RESOURCES

Four areas with potential for discovery or development of low-temperature geothermal waters (less than 100 °C) have been identified in the Sonoran region of Arizona (Witcher and others, 1982). These areas, about 104–777 km^2, are located in the southern Sacramento Valley near Yucca, west of the Aquarius Mountains in the Big Sandy River valley, along the Santa Maria River east of Alamo Crossing, and in the Ranegras Plain west of Vicksburg. Three thermal wells in the study area have water temperatures that exceed 50 °C. Only one well, with a water temperature of 89 °C, is in an area with a gradient greater than 15 °C/km. The majority of the geothermal wells are shallow and produce water with a temperature less than 50 °C. There are few thermal springs in the region, none of which have temperatures in excess of 50 °C. There are no Known Geothermal Resources Areas in the Sonoran region of Arizona (Witcher and others, 1982).

COAL, OIL, AND GAS RESOURCES

No coal occurrences have been identified in the Sonoran region of Arizona. A few wildcat oil and gas boreholes have been drilled in the study area (Conley and Stacey, 1981; Brady, 1983); however, no production has been recorded to date. The potential for oil and gas discoveries in southwestern Arizona has been described by McCarthy (1961) and Peirce and others (1970), and for the recently publicized overthrust oil and gas reserves, by Anschutz (1980) and Reif and Robinson (1981). Oil and gas potential is unknown except perhaps for basin-fill sand along the lower Colorado River trough. In the Yuma basin, for example, leasing was active following the drilling by Pemex of a commercial gas well in the adjacent northwestern part of Sonora, Mexico, near the mouth of the Colorado River (World Oil, 1981; Davis, 1981). There, Pemex announced a preproduction flow of 5.7 million m^3/d of gas from a depth of 4,115 m in Miocene and Pliocene sands. These sands may extend northward, thinning toward the Yuma area.

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