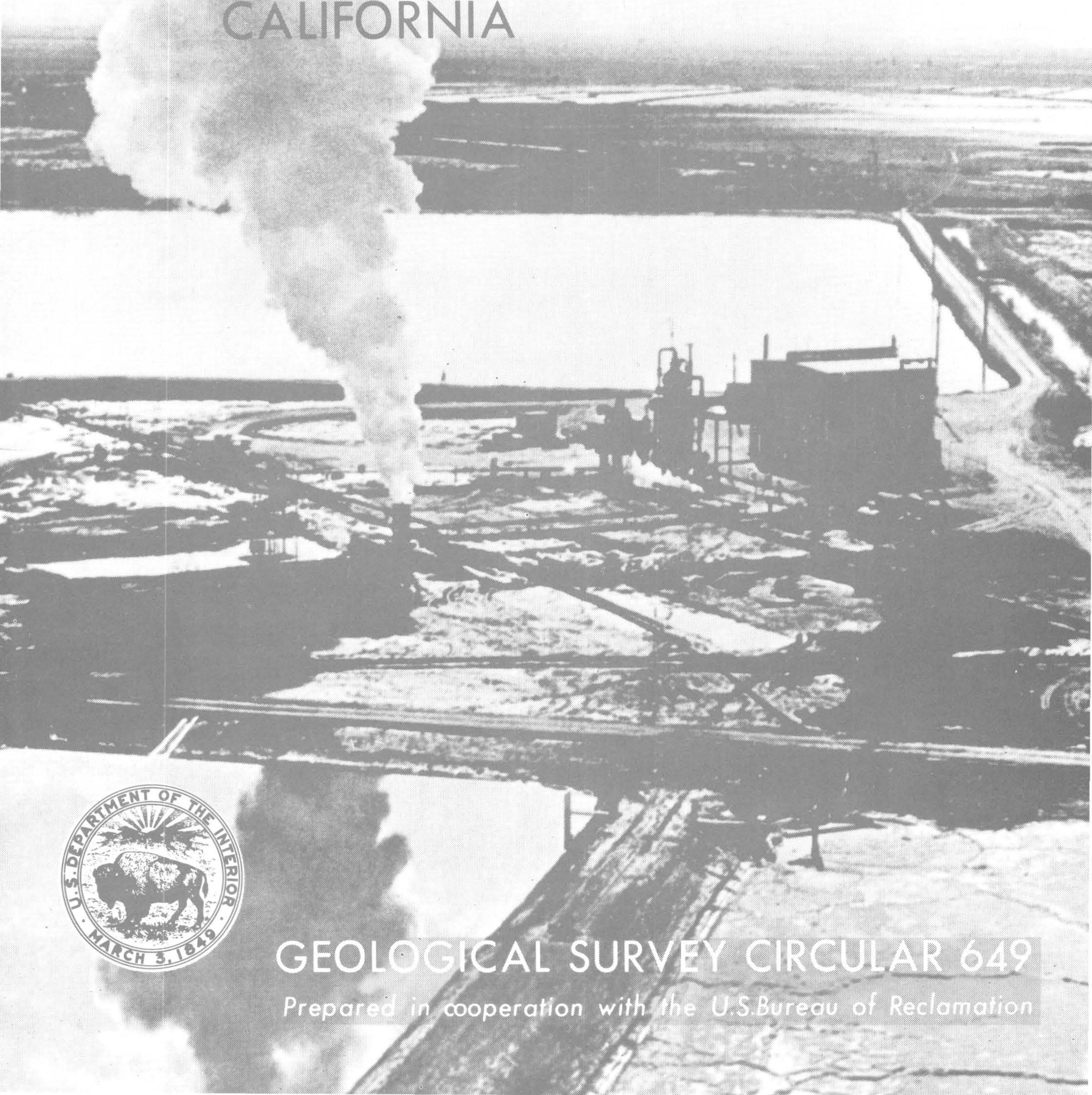
PRELIMINARY APPRAISAL OF GROUND WATER IN STORAGE WITH REFERENCE TO GEOTHERMAL RESOURCES IN THE IMPERIAL VALLEY AREA, CALIFORNIA



GEOLOGICAL SURVEY CIRCULAR 649

Prepared in cooperation with the U.S. Bureau of Reclamation

Preliminary Appraisal of Ground Water in Storage With Reference to Geothermal Resources in the Imperial Valley Area, California

By L.C.Dutcher, W.F.Hardt, and W.R.Moyle, Jr.

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CONTENTS

ILLUSTRATIONS

COVER. Photograph courtesy of the Imperial Irrigation District.

TABLES

Preliminary Appraisal of Ground Water in Storage With Reference to Geothermal Resources in the Imperial Valley Area, California

By L. C. Dutcher, W. F. Hardt, and W. R. Moyle, Jr.

ABSTRACT

Imperial Valley occupies part of a deep sediment-filled structural basin that extends south from the Coachella Valley in California to the Gulf of California. The Gulf of California coincides with the intersection of the East Pacific rise and the North American Continent, and heat flow through the thick (as much as 20,000 ft) young water-saturated sediments deposited in the delta of the Colorado River is greater than the world-wide average. Superimposed on the broad heat-flow anomaly are several small areas that have heat flow 4–10 times average. Electric power will soon be generated using geothermal energy at Cerro Prieto, Mexico. Deep wells at the Salton Sea geothermal field near Niland, Calif., have been tested for electric power production, but because the very hot water contains about 260,000 mg/l (milligrams per liter) dissolved solids, commercial production of electricity is not yet economically feasible.

Because of the extremely high temperatures at depth throughout the basin and at relatively shallow depth in areas of anomalously high heat flow, the deposits are undergoing metamorphism. The active metamorphism has caused changes in the original porosity and permeability of the rocks and deposits.

Temperature gradients range from about 1° to 3°C per 10 feet through most of the sediments where heat flow is dominantly by conduction, but in some exceptional areas the gradients range from 7° to 10°C or more per 100 feet. Where heat flow is dominated by water convection in deep cells, the geothermal gradients are only slightly below the pressure reference boiling-point curve for the brine solution. The temperature is probably slightly below the boiling curve because of partial pressures of gasses in the system.

Our conceptual model of the hydrothermal system mechanisms includes recharge to the deep convection cells for about 50,000 years at a rate of about 30 liters per second. The discharge is mainly flow in the vapor phase through fractures into overlying shallow aquifers or to the surface. According to our conceptual model, the dissolved minerals in the recharge water are accumulated in the brine of the deep convection cells. Thus, the salinity of the deep water is dependent on the recharge-discharge rate, the duration of flow, and the salinity of the inflowing water. On the basis of preliminary data and the conceptual model, wherever the salinity of the recharge water from the base of overlying shallower aquifers exceeds about 4,000–5,000 mg/l, the salinity of deep brines in convection cells may exceed 35,000 mg/l.

Estimated porosity and specific yield of the deposits were used to estimate recoverable water. The percentage of recoverable water in storage ranges from an average of about 5 percent of the volume for deposits at depths greater than 8,000 feet to about 20 percent of the volume for shallow deposits in the ground-water recharge area.

The total usable and recoverable water in the Imperial Valley is estimated to be 1.1 billion acre-feet, of which about 200 million acre-feet is at a temperature of 150°C or greater. This estimate includes water probably containing less than 35,000 mg/l dissolved solids regardless of temperature. About 62 percent of the total usable and recoverable water was derived from the Colorado River and about 38 percent from local sources.

The combination of low well yields, energy costs in excess of $100 per acre-foot for lifts greater than 5,000 feet, and very high capital costs of wells will probably prevent pumping most of the estimated usable and recoverable water. If as much as 1,000 feet of pumping lift would be economically justified, about 100 million acre-feet of water might be recoverable from the shallow aquifers.

Thus, economic studies are needed to determine the feasibility of recovering the estimated 1.1 billion acre-feet of water. Such studies may indicate that usable and recoverable water is only about 100 million acre-feet at a temperature less than 100°C, and less than 200 million acre-feet at higher temperatures.

The probable percentage error for the estimates of water in storage cannot be determined because data are not available. Therefore, the logic on which great extrapolations of meager data could be based had to be developed by formulating a conceptual model of the sedimentary basin and by considering the elements and

mechanisms of the hydrothermal system. Thus, the accuracy of the estimates of usable and recoverable water in the system is directly related to how adequately the conceptual model of the system represents the prototype. Only further drilling, testing, experiments, and studies can provide a firmer basis for determining what amount of water can be recovered economically.

As in other heavily pumped basins of the arid West, extractions in Imperial Valley that cause water levels to decline to new low levels each year will cause continuing surficial subsidence. In parts of the valley long-term subsidence might be of little consequence; in other areas damages would probably be prohibitive. Large-scale water production or injection, particularly involving the deep high-temperature rocks, may constitute a seismic hazard; this problem will require extensive research.

Questions of noise generation, air pollution, and water pollution also will require answers prior to large-scale development of the potential resource.

INTRODUCTION

GENERAL GEOLOGIC AND HYDROLOGIC SETTING

Imperial, Mexicali, and Coachella Valleys occupy the sediment-filled northern extension of the deep structural basin occupied on the south by the Gulf of California. Imperial Valley is the name given to the large part of the basin south of the Salton Sea in the United States. The southern part of the basin in Mexico is called Mexicali Valley (fig.1). North of the Salton Sea the basin is called Coachella Valley.

The entire depression is commonly called the Salton Trough and is filled primarily with clay, silt, and find-grained sand deposited by the Colorado River as part of its delta (Muffler and Doe, 1968).

Under natural conditions ground-water recharge to the basin, both in the United States and in Mexico, was largely from fresh-water runoff in the Colorado River. But some recharge was derived from precipitation on the bordering uplands along the east and west basin margins. All ground-water discharge was by evapotranspiration from the shallow water table beneath the basin floor or, at times when large or small lakes existed in the basin, by inflow to shallow lakes. Since 1900 large-scale irrigation using water imported from the Colorado River has caused changes in the ground-water recharge and discharge relations.

The Gulf of California coincides with the intersection of the East Pacific rise and the North American Continent. The general positive heat-flow anomaly of the East Pacific rise extends north at least the full length of the Salton Trough. The few available measurements of heat flow in the central and southern parts of the Gulf of California average about 3.3 microcal/cm^2/sec (microcalories per square centimeter per second) (Von Herzen, 1963), more than doubled the oceanic average of about 1.5 microcal/cm^2/sec. However, a reasonable average background conductive heat flow in the continental part of the Salton Trough may be about 1.7 microcal/cm^2/sec (A. H. Lachenbruch written commun., 1971). Superimposed on the broad heat-flow anomaly are several small areas that have heat flow 4–10 times average (Rex, 1966). The high heat flow has created greater than average geothermal gradients. There are two known areas of Quaternary volcanism and several local areas of hot-spring activity. The high geothermal gradients in the thick young water-saturated detrital sediments have created a potential geothermal energy resource that might be extensively exploitable. The Mexican Government has explored one area at Cerro Prieto, Baja California, Mexico, about 25 miles southeast of Mexicali (fig. 2) for geothermal energy (Alonso Espinosa and Mooser, 1964; Anda and Paredes, 1964). Development of a major steam field is underway for electric power production. The capacity of existing wells is reported by Rex (1970, p. 5) to be great enough to supply steam for 100-megawatts of power; a plant is now under construction to produce about 75 megawatts.

A second area of anomalous heat flow is in the United States at the Salton Sea geothermal field, sometimes called the Obsidian Buttes field or the Niland field. Exploration has consisted of deep drilling and pilot production of water and steam from several wells (Helgeson, 1968; Muffler and White, 1969). Because the water at the Salton Sea field is highly saline—as much as 260,000 mg/l (milligrams per liter) dissolved solids—technical problems, mainly due to its highly corrosive nature, have deterred commercial production of electricity and recovery of minerals from the brine.

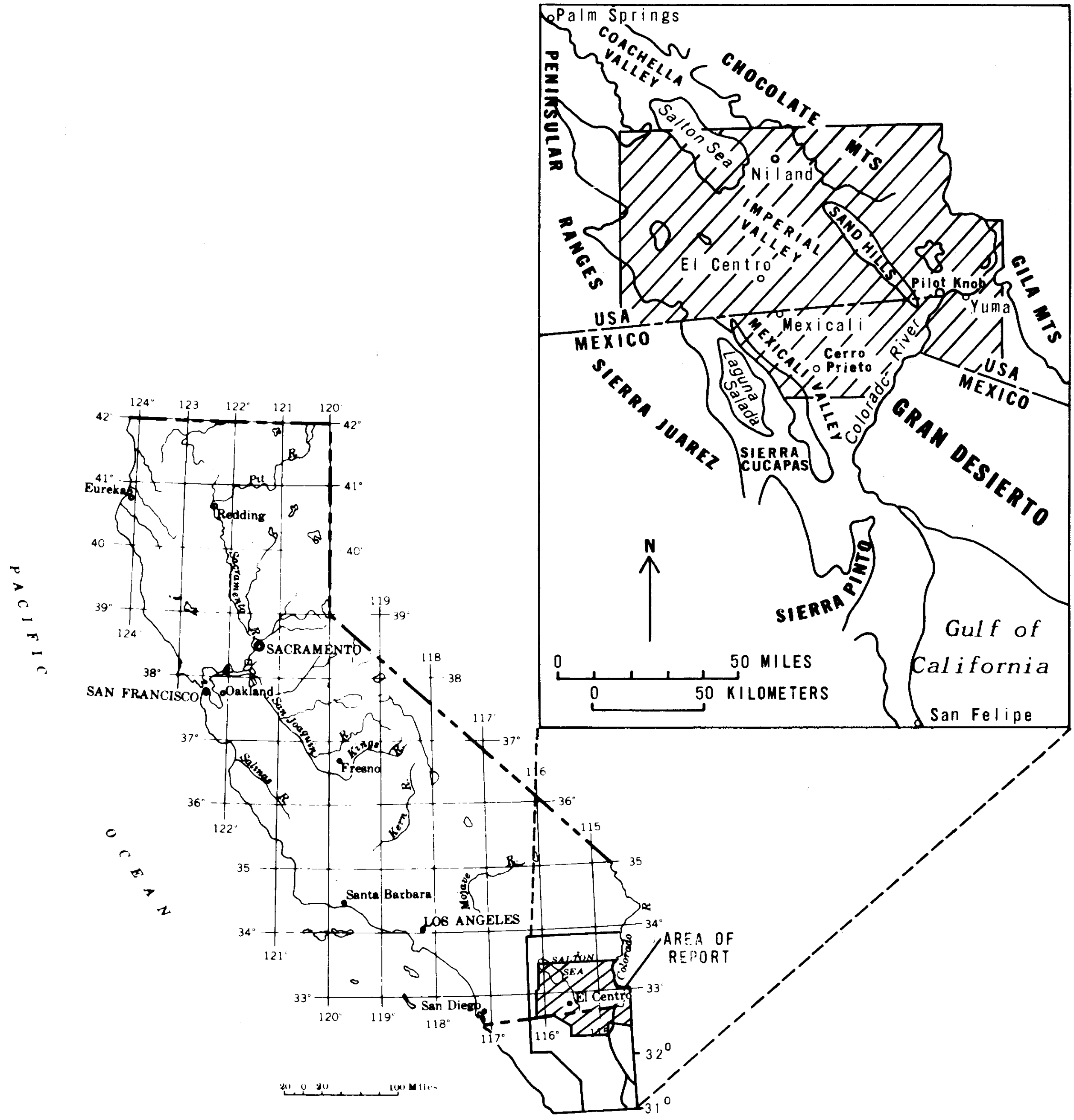


FIGURE 1.—Index map.

Nevertheless, the large deep structural basin filled with low to moderately permeable rocks having substantial porosity and therefore containing a substantial quantity of water in an area of higher than average heat flow has created widespread interest in the Salton Trough geothermal basin. Research and exploration of the gothermal, water, and chemical resources of the basin are being continued by public and private agencies. The goal is to determine the extent and value of the resources and the technical means of their economic use.

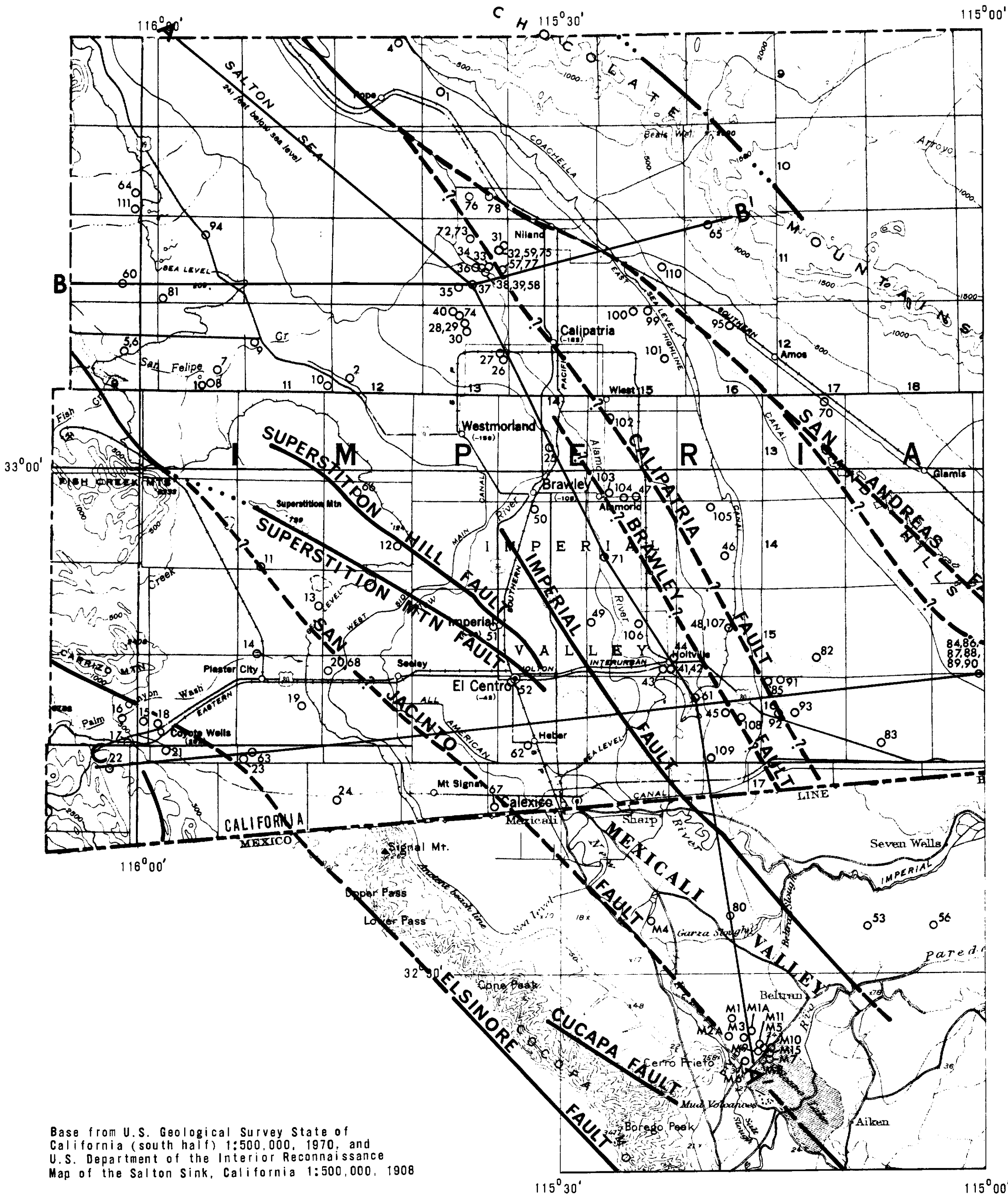


FIGURE 2.—Location of wells, springs, and hydrologic sections in Imperial and Mexicali Valleys.

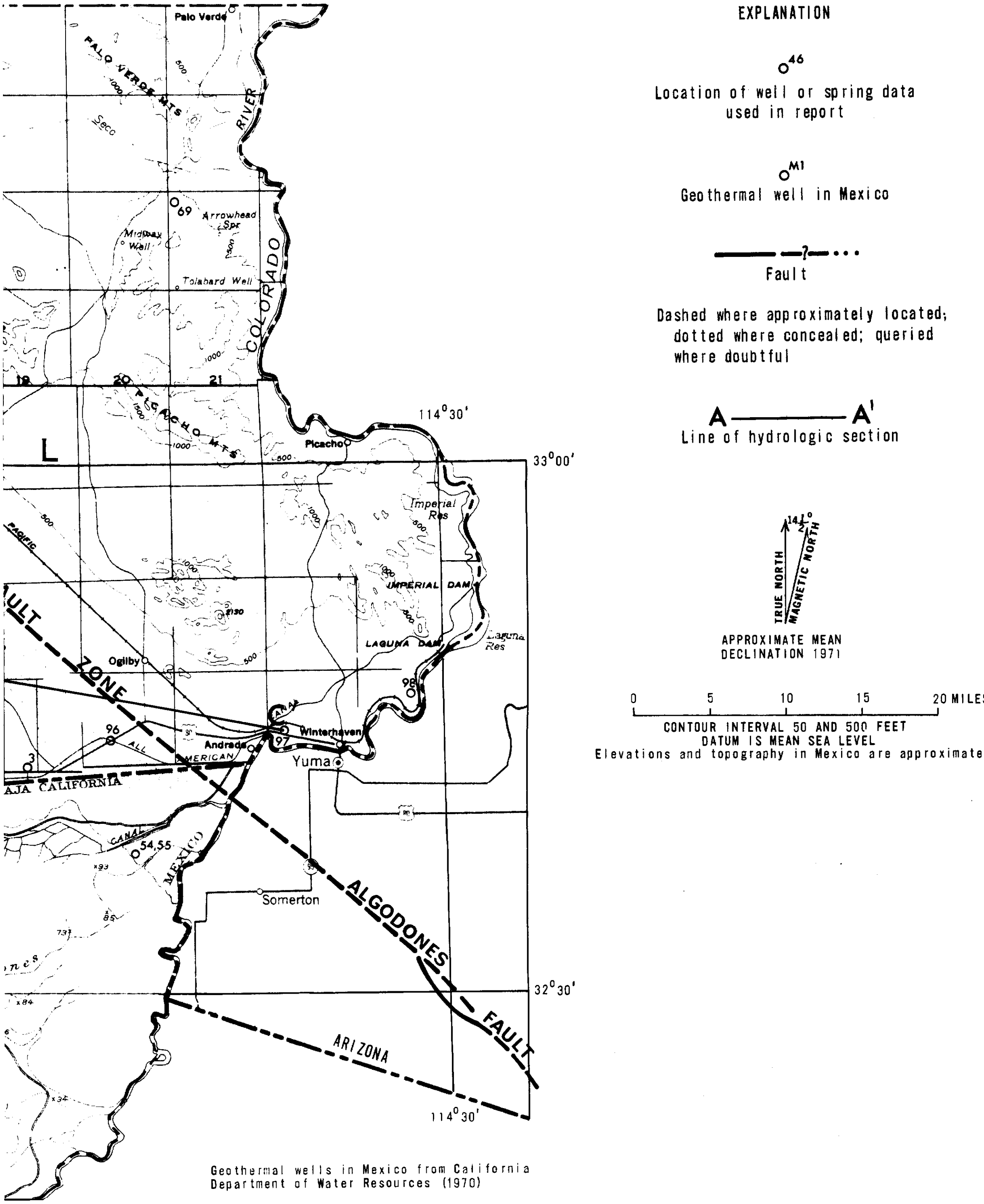


FIGURE 2.—Continued.

PREVIOUS WORK AND REPORTS

The earliest geohydrologic studies of the Imperial Valley were in the early 1900's and consisted of soil surveys (Holmes and party, 1930; Strahorn and others, 1922; and Kocher and others, 1923) of the Imperial Valley, El Centro, and Brawley areas, respectively. Early water studies consisted mainly of locating and describing springs and wells (Mendenhall, 1909, and Brown, 1920). The first reconnaissance report of the geohydrology of the Salton Sea region was by Brown (1923).

From these early reconnaissance studies, the geohydrology of Imperial and Coachella Valleys—the Salton Trough section of the Basin and Range physiographic province of Fenneman (1931)—has been studied in increasing detail. Significant geologic studies of the Salton Trough were made by Tarbet and Homan (1944), Tarbet (1951), Dibblee (1954), Woodard (1961), Durham and Allison (1961), Downs and Woodard (1961), Merriam and Bandy (1965), and Morton (1972).

West of the Salton Trough, the Peninsular Range province has been studied by Larsen (1948), Beal (1948), Jahns (1954), and Merriam (1958). The geology of the mountains on the north and east were described by Bailey and Jahns (1954), Rogers (1961), Crowell (1962), and Olmsted, Loeltz, and Ireland (1972).

Several water-resources studies of the Salton Sea area have been of particular value: Bradshaw and Donnan (1952), California Department of Public Works (1954), Hely and Peck (1964), Hely, Hughes, and Irelan (1966), Rex (1968), California Department of Water Resources (1970), and O. J. Loeltz (written commun., 1971). Water-level measurements and chemical analyses are tabulated in California Department of Water Resources Bulletins 39 and, since 1956, 130 series.

The discovery of the geothermal resources at Cerro Prieto, Mexico, and the high temperature hypersaline brine at the Salton Sea geothermal field stimulated a great increase in scientific study of the area and in research related to the extent and mode of occurrence of the geothermal and mineral resources. Numerous papers have been published in recent years on a broad scope of subjects.

The published geologic studies have been related prinicipally to the geology of the Colorado River delta deposits (Muffler and Doe, 1968; Merriam and Bandy, 1965; and Sykes, 1937a, b) and active metamorphism of the sediments (Muffler and White, 1969; White and Muffler, 1965). Biehler, Kovach, and Allen (1964), Kovach, Allen, and Press (1962), Biehler (1964), Rex (1970), and Griscom and Muffler (1971) studied the geophysical framework; Helgeson (1968) studied the geologic and thermodynamic characteristics; Allison (1964) studied the geology of the bordering areas; Arnal (1961) studied the sedimentation and fossils; Dibblee (1954) mapped the valley sediments; Kelley and Soske (1936) discussed the volcanic domes near the Salton Sea; and Robinson and Elders (1970) discussed xenoliths in the volcanic rocks.

The mineralogical studies have included the hydrothermal minerals (Keith and others, 1968), sulfide minerals (Skinner and others, 1967), base-metal ore deposits (White, 1968), and silicate metamorphism and genesis of ore solutions (Helgeson, 1967a).

Aspects of the water quality and chemistry of the geothermal brines are included in several papers published since 1940. Included in these are descriptions of solution chemistry (Helgeson, 1967b); possible sources of lead and strontium in geothermal basins (Doe, Hedge, and White, 1966); origin of carbon dioxide and description of carbon dioxide wells in the system (Muffler and White, 1968; Rook and Williams, 1942; and Lang, 1959); general character of the Salton Sea geothermal brines (White, Anderson, and Grubbs, 1963; White, 1968); sources of the water (Craig, 1966, 1969; Berry, 1966, 1967; and Craig and Gordon, 1965); and oxygen isotopes of rocks and water (Clayton and others, 1968; White, 1968).

Aspects of temperature and heat flow in the region have been described by White, Muffler, and Truesdell (1971); Rex (1966); Helgeson (1968); Koenig (1967, 1969, and 1970); Menard (1960); Von Herzen (1963); McNitt (1963, 1965); and Alonso Espinosa and Mooser (1964).

Several studies have recently been completed that deal mainly with prospects for developing the water, mineral, and geothermal resources of that part of the Salton Trough within the United States. In two of these papers (White, 1968; Berry, 1966) the authors developed conceptual models of part of the geothermal system. Koenig (1967) described the resources in general terms. The potential geothermal resource of the Salton Trough was analyzed by Rex (1970). In that paper the author stated that it is feasible to develop 10–15 million acre-feet of geothermal brine annually, yielding 5–7 million or more acre-feet of distilled water and 20,000–30,000 megawatts of electric power. He also estimated that the volume of water in storage within the United States but south of Westmoreland, Calif., and excluding the hypersaline brine, is 1.6–4.8 billion acre-feet (Rex, 1970, p. 14).

Finally, the U.S. Bureau of Reclamation (1971) summarized the work of Koenig (1967) and Rex (1970) and outlined a proposed program of additional studies and pilot projects.

PURPOSE AND SCOPE OF THIS REPORT

The primary purpose of this study, within the time and funds available, was to estimate the total recoverable water in storage in the sedimentary basin having dissolved-solids concentration equal to or less than that of sea water (approximately 35,000 mg/l). Because the term "recoverable water" could mean very different things in different engineering and economic contexts, it was decided that the estimate should include all water in storage which could probably be withdrawn from wells, considering present water-use patterns and practices, without regard to water temperature or content of specific ions. The estimate of recoverable water in storage was made without regard to costs or to the number and spacing of required production or injection wells; thus, it does not consider important economic and engineering factors. The time and funds available for the work did not permit a thorough evaluation of the environmental or hydrologic consequences of removing all or part of the water from storage in the basin. A brief discussion of such consequences is included, however.

Three secondary purposes of this study were to estimate the following: (1) The percentage of the total recoverable water in storage that underlies Federal Lands in Imperial Valley which have been withdrawn from the public domain for reclamation purposes—the Imperial Valley is being considered as a potential source of water to augment the Colorado River supply, (2) the total water in storage having a temperature greater than approximately 150°C, and (3) the total recoverable water in storage derived from both the Colorado River and local sources in California.

The scope of the work included:

1. Collecting for analysis and study pertinent available geologic, geophysical, and hydrologic data for the area, including logs of wells.
2. Analyzing available data and formulating a conceptual geologic and hydrologic model of the sedimentary basin.
3. Compiling an estimate of the basin's total recoverable water containing 35,000 mg/l, or less, dissolved solids.
4. Describing the possible hazards that might accompany water production, including land subsidence, possible seismic activity, and changes in the water inflow-outflow relations of the basin.
5. Appraising the accuracy of the estimates of recoverable water and describing the additional data needed to refine the estimates.
6. Preparing a report summarizing the results of the study.

All the foregoing work was accomplished between May 20 and July 10, 1971; thus, the results presented herein are preliminary and should be regarded as subject to revision.

This report was prepared by the U.S. Geological Survey in cooperation with the U.S. Bureau of Reclamation as part of an investigation of the water resources of the Imperial Valley area. The work was done during 1971 under the general direction of R. Stanley Lord, district chief in charge of water-resources investigations in California.

ACKNOWLEDGMENTS

We are greatly indebted for discussions and consultation with many individuals and colleagues during this study. We have had immense benefit from such discussions with our colleagues D. E. White, L. J. P. Muffler, Ivan Barnes, Alfred Clebsch, Jr., J. H. Feth, and P. H. Jones of the U.S. Geological Survey.

We are greatful for the help of Mr. Bill Creel, Schlumberger Well Services, Inc.; Mr. Kent Crowder, Standard Oil Co. of Calif.; and many representatives of commercial oil companies who also supplied data for wells; and for the assistance given by J. B. Combs and Walter Randall, staff scientists at the University of California, Riverside, and R. T. Littleton of the Bureau of Reclamation.

We are especially greatful for the assistance of O. J. Loeltz, U.S. Geological Survey, Yuma, Ariz., who supplied much data, helped with analysis and interpretation of data, and assisted with the computations, as did W. R. Powers III of the Garden Grove office.

Special thanks and recognition is due Ben E. Lofgren, U.S. Geological Survey, Sacramento, Calif., who wrote the section "Land Subsidence" in the report.

Without the enormous help, assistance, and data supplied by these individuals the report could not have been completed. These acknowledgements of course do not commit any of the above individuals to views and interpretations expressed herein.

SOURCES AND ADEQUACY OF DATA

Time was not available for new fieldwork during this study. A detailed study was made of previous publications (see section "Previous Work and Reports"), and discussions were held with personnel of the U.S. Bureau of Reclamation, Boulder City, Nev.; Institute of Geophysics and Planetary Physics, University of California at Riverside; Schlumberger Well Services, Inc.; selected oil companies; and personnel of the U.S. Geological Survey.

The sources of data included a primary network of about 50 deep oil exploration and geothermal wells, supplemented with about 75 shallow water wells and springs. Figure 2 shows locations of wells and springs and hydrologic sections.

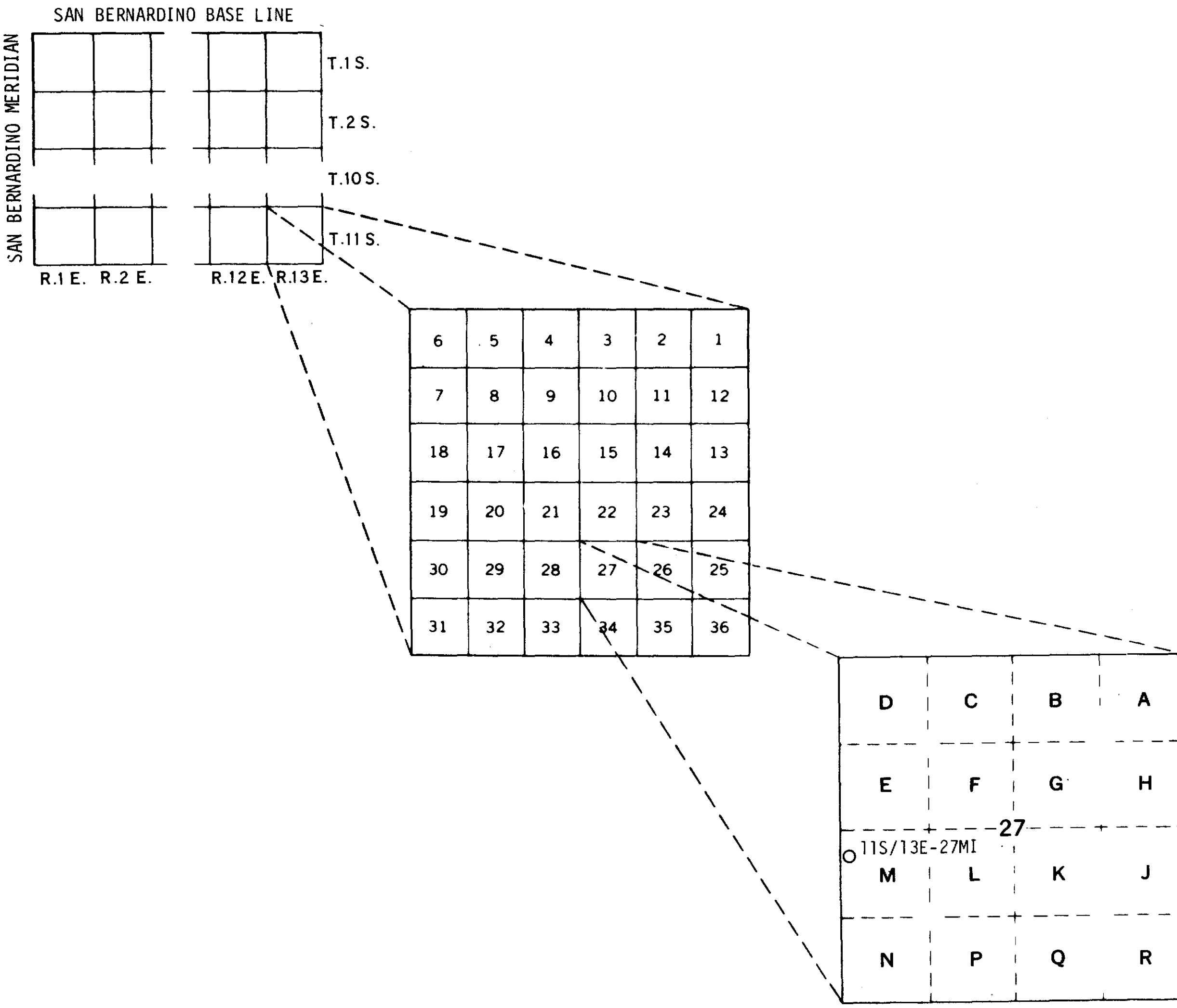
Electric logs were available for many of the deep wells, but other geophysical logs, such as neutron porosity, neutron, sonic, gamma-gamma, and temperature logs were available for only a few wells. Only a few chemical analyses of water from the deeper zones of the basin sediments were available. Temperature logs were helpful but not always indicative of the true formation temperature. Data from the water wells consisted of drillers' logs, water-level measurements, and chemical analyses. Without the data from many shallow wells, analysis of the deeper geothermal zones would have been more difficult.

The previously mapped surface geology (fig. 3) was used in this study. Of prime importance was the delineation of the boundary between the water-bearing materials of the ground-water basin and the areas of non-water-bearing igneous and metamorphic rocks of the mountains. The map of thickness and configuration of the basin sediments as determined by Rex (1970) was used for this study (fig. 4), and his map was utilized in virtually unchanged form.

In appraising the adequacy of data for subsurface analysis, it became apparent that although numerous reports have been prepared they are based on a paucity of basic data. Many of the reports were keyed to a few selected data, and the authors reached various conclusions. Much of the inadequacy of the data is largely the result of extremely high formation temperatures encountered during drilling.

WELL- AND SPRING-NUMBERING SYSTEM

Wells and springs (fig. 2) are numbered according to their location in the rectangular system for the subdivision of public land. For example, in the number 11S/13E–27M1, the part of the number preceding the slash indicates the township (T. 11 S.), the part between the slash and the hyphen indicates the range (R. 13 E.), the number between the hyphen and the letter indicates the section (sec. 27), and the letter indicates the 40-acre subdivision of the section. Within the 40-acre tract wells are numbered serially, as indicated by the final digit. Thus, well 11S/13E–27M1 is the first well to be listed in the NW¼SW¼ sec. 27, T. 11 S., R. 13 E., San Bernardino base line and meridian as shown in the following diagram.



Geothermal wells in Mexico are preceded by the letter M and numbered serially. These numbers were retained from previous reports.

Springs are numbered similarly to wells except that an S is placed between the 40-acre subdivision letter and the final digit as shown by the following spring number: 11S/13E-24ES1.

GEOLOGY

SETTING

The southern part of the Salton Trough in the United States is called Imperial Valley. The Salton Sea (fig. 1) is about 30 miles long and 10 miles wide and occupies the lowest part of the trough (232 ft below mean sea level in 1968). The crest of the Colorado River delta in Mexicali Valley protects the Salton basin from inundation by water from the Gulf of California. The land surface slopes northwest from about sea level at the international boundary to the Salton Sea. The shoreline of prehistoric Lake Cahuilla is well preserved along the east and west sides of the valley at 42–50 feet above mean sea level.

Imperial Valley is bordered on the west by the Peninsular Ranges, which are mostly granitic rocks (figs. 1, 3) of probable Cretaceous age (Dibblee, 1954, p. 21). On the east are the Chocolate Mountains, which in the northern part are principally plutonic and metamorphic rocks, of pre-Tertiary age, and to the south are extensive volcanic rocks of Ter-

FIGURE 3.—Geologic map of Imperial and Mexicali Valleys.

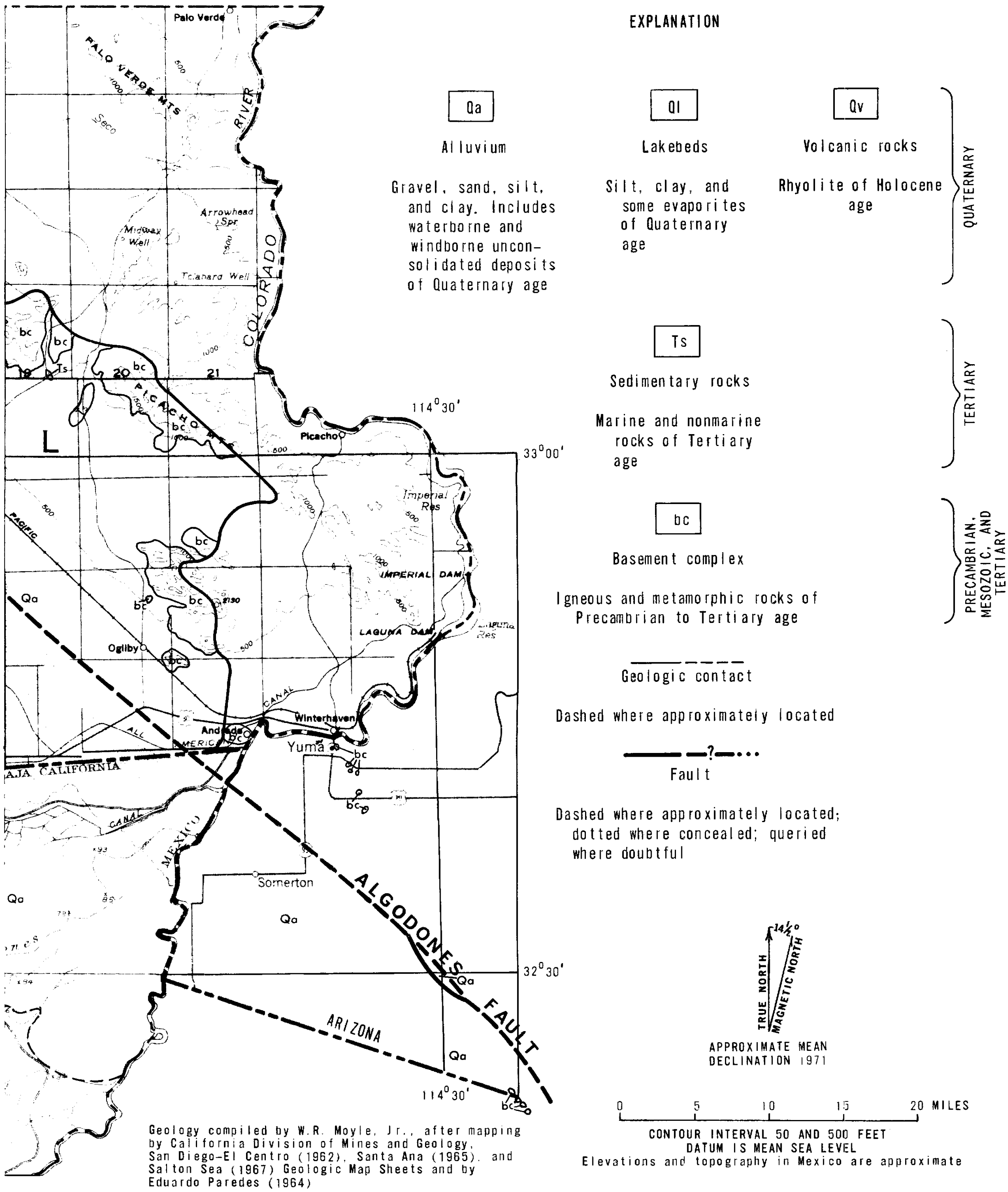


FIGURE 3.—Continued.

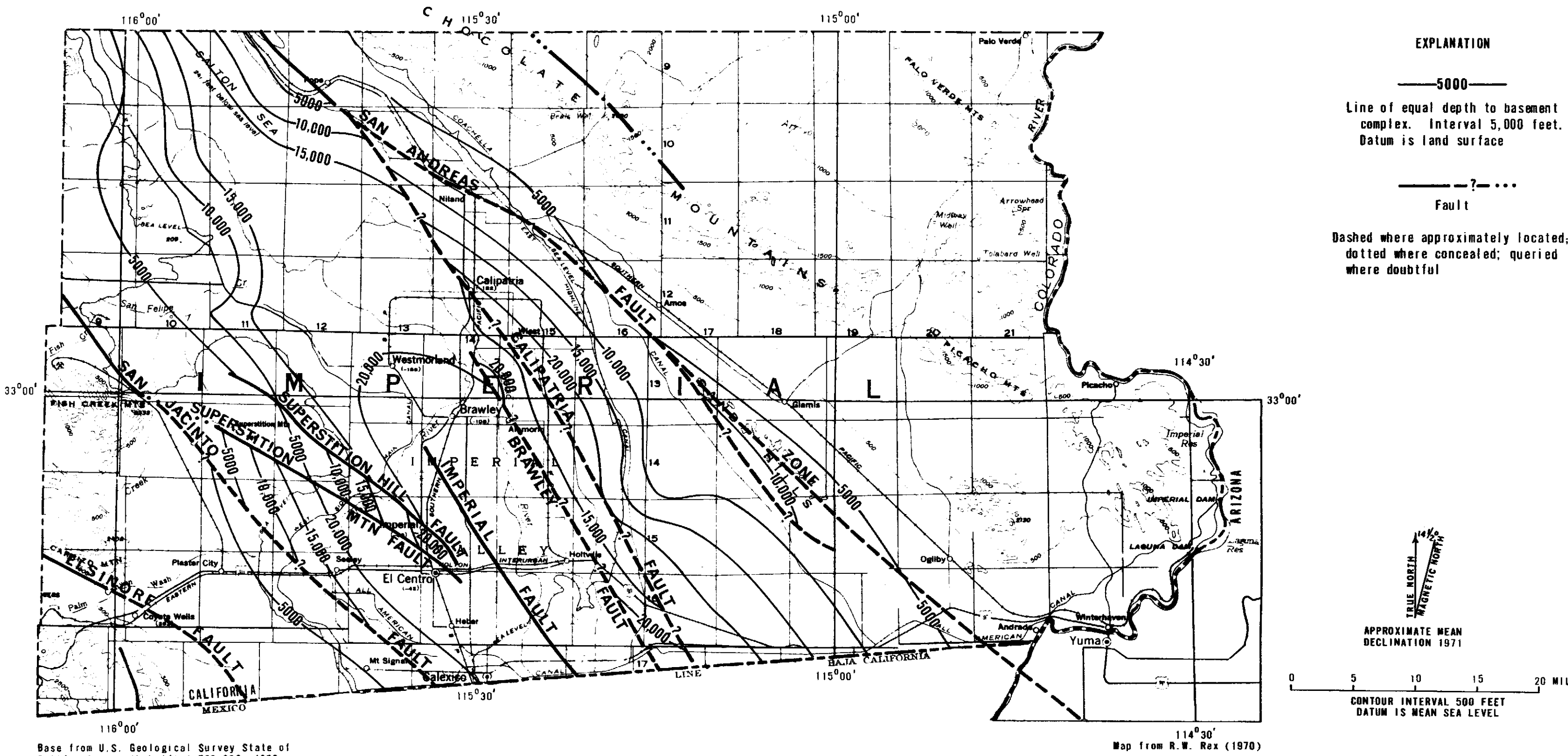


FIGURE 4.—Depth to basement complex.

tiary age. The valley between the mountains is identified from east to west by local residents as the Sand Hills, East Mesa, main valley, and West Mesa areas (see fig. 16).

The Sand Hills (Norris and Norris, 1961) along the east valley margin are more than 40 miles long and as much as 6 miles wide. These hills lie on the surface sloping southwest to west. In the southwest part of the area there are longitudinal southeast-trending sand ridges as much as 300 feet above the adjacent mesa surface.

The East Mesa area is a triangular area between the Coachella and East Highline canals. The area was formed by fluvial processes, locally modified by lacustrine or marine processes, and merges gradually with the main valley.

The main valley area consists primarily of cultivated agricultrual land and is entirely within the shorelines of prehistoric Lake Cahuilla. The soils from the lakebed materials contain a large proportion of clay and silt of low permeability, in contrast to the sandy soils of the adjacent East and West Mesas.

The Alamo and New Rivers are the two main drainages to the Salton Sea and have cut trenches as much as 40 feet deep, mostly during 1905–07 when the Colorado River flowed uncontrolled across the valley floor to the lake then formed. Obsidian Butte, Red Island, Rock Hill, and Mullet Island are small domical hills 20–100 feet above the general surface along the southeast shore of the Salton Sea.

West Mesa is a broad plain between the main valley and the Peninsular Ranges to the west. Many ephemeral streams drain this area. The soil is sandy and has less clay than in the central part of the valley.

STRUCTURE

Three major right-lateral fault zones strike into Imperial Valley (fig. 3). The San Andreas fault zone (also called the Mission Creek-Banning fault zone) strikes along the east side of the valley, and the Elsinore and San Jacinto faults have been mapped along the west margin.

The position of the San Andreas fault zone has been inferred on the basis of an alinement of anomalously low gravity measurements that extend from the Salton Sea southeastward to the Colorado River. The gravity data are supported by seismic-refraction profiles (Kovach, and others, 1962) and aeromagnetic profiles (Griscom and Muffler, 1971). That fault, or possibly a parallel fault, has been traced into Arizona, south of Yuma, by Olmsted, Loeltz, and Irelan (1972), where it is named the Algodones fault.

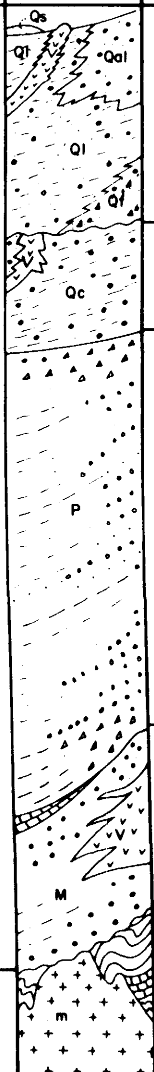
The Elsinore fault is the southwesternmost right-lateral fault related to the San Andreas system in the United States (Biehler and others, 1964, p. 139). The vertical component of movement on the fault is as much as 3,000 feet northwest of Imperial Valley (Jahns, 1954, p. 45). This fault extends into Baja California and is locally called the Laguna Salada fault.

The San Jacinto fault, which is related to the San Andreas fault system, splits into several subparallel faults west of Imperial Valley. The Superstition Hill and Superstition Mountain faults are probably part of this system. Imperial fault may be a part of this system (Biehler and others, 1964, p. 138). As much as 13 feet of right-lateral movement occurred on the Imperial fault east of Calexico during the earthquake of May 18, 1940 (Dibblee, 1954, p. 26).

The Calipatria and Brawley faults in the central valley were shown on maps by Rex (1970). The mapping was based on unpublished work by E. A. Babcock (written commun., 1969). Gravity surveys across the basin (Kovach and others, 1962, p. 2869–2870) were not particularly successful in demonstrating the continuity of major fault zones within the trough, although these data confirm the presence of large vertical displacements beneath the valley alluvium. For this study, the Calipatria and Brawley faults are shown where postulated by previous workers, although further work is needed to substantiate their existence and effect on the basin-filling rocks and deposits, and especially to determine their effects on ground-water circulation.

STRATIGRAPHY

The clastic sediments filling Imperial Valley represent almost continuous deposition since Miocene time (fig. 5). The sediments were derived mainly from the Colorado River drainage

Geologic Age	Stratigraphic column	Stratigraphic unit and symbol	Stratigraphic nomenclature*	Maximum thickness (feet)	DESCRIPTION
QUATERNARY		Dune Sand (Qs)	Recent Dune Sand	300 (Dune Sand to Terrace Deposits)	Wind-blown sand, local dunes. Locally distributed around Salton Sea
		Alluvial Deposits (Qal)	Recent Alluvium		Gravel, sand, silt, and clay. Occurs along river channels and at foothills above the ancient shoreline of Lake Coahuila
		Volcanic Rocks (V)	Recent Volcanic Rocks		Obsidian, rhyolite, and pumice composing volcanic domes on the southeast shore of Salton Sea. Locally interbedded obsidian flows and lake deposits.
		Lake Deposits (Ql)	Lake Coahuila (*Cahuilla*) Deposits		Clay, silt, sand, beach gravel, and evaporite deposits of the former extensive lake. Includes older lake beds above ancient shoreline of Lake Coahuila and locally undifferentiated alluvial deposits.
		Terrace Deposits (Qt)	Quaternary Nonmarine Terrace Deposits		Extensively dissected and locally folded stream terrace deposits of fanglomerate, gravel, and sand, in Borrego Valley.
		UNCONFORMITY			
		Nonmarine Sediments (Qc)	Brawley Formation	2,000	Red-grey claystone, siltstone, sandstone, and pebbly gravel deposits.
			Ocotillo Conglomerate	2,500	Grey, poorly consolidated boulder conglomerate, grading basinward into pink sandstone and claystone. Distributed generally in forebay areas along foothills.
		Volcanic Rocks (V)	Pleistocene Volcanic Rocks	--	Quaternary rhyolite plugs along Salton Creek.
TERTIARY		Pliocene Formations (P)	Unnamed Pliocene-Pleistocene Nonmarine Sedimentary Deposits	--	Moderately deformed fanglomerate in the northern Chocolate Mountains, consisting of unsorted, poorly consolidated, pale grey-yellow sediments containing mostly angular volcanic clasts.
			Canebrake Conglomerate	9,000	Grey conglomerate and fanglomerate of granitic and metamorphic debris. Unsorted and poorly consolidated. Continental origin.
			Palm Spring Formation	7,000	Light-grey arkosic sandstone and reddish claystone, grading into Canebrake conglomerate. Continental origin. Contains Pliocene and/or Pleistocene vertebrate fossils west of Salton Sea.
			Borrego Formation	6,000	Light-grey claystone and minor amounts of buff sandstone of lacustrine origin; contains a lacustrine fauna of minute mollusks, ostracods and rare foraminifera; grades laterally into Palm Spring formation.
			Mecca Formation	1,000	Greyish-red to yellowish-brown basal conglomerate, overlain by arkose and arkosic conglomerate of granitic and metamorphic debris. Continental origin.
			Imperial Formation	4,000	Light-grey claystone and lessor interbedded arkosic sandstone with calcerous oyster-shell "*reefs*." Shallow-water, marine in origin.
		Miocene—Eocene Formations (M)	Split Mountain Formation	2,700	Red or grey cemented basal conglomerate or fanglomerate and sandstone of granitic and metamorphic debris. Overlain locally by gypsum and anhydrite beds (Fish Creek Gypsum member). The upper member is marine, while the middle and lower members are nonmarine in origin.
			Unnamed Oligocene Nonmarine Sedimentary Rocks	--	Conglomerate, sandstone, breccia, mudstone, and evaporite rocks (Orocopia Mountains).
			Maniobra Formation	--	Marine Eocene, siltstone, sandstone, conglomerate, and breccia with some sandy limestone (Orocopia Mountains).
		Volcanic Rocks (V)	Undifferentiated Tertiary Volcanic and Intrusive Rocks	--	Local lava flows and tuffs. Flows are andesitic, rhyolitic, or basaltic rocks of various ages. Also includes intrusive acidic rocks and related diabasic dikes. Alverson andesite dated as Miocene.
		UNCONFORMITY		20 000 (Brawley Formation to Undifferentiated Tertiary Volcanic and Intrusive Rocks)	
PRE-TERTIARY		Granitic and Metamorphic Rocks (m)	Undifferentiated Mesozoic Granitic Rocks	--	Granitic rocks.
			Orocopia Schist	--	Pre-Cretaceous schist.
			Other Pre-Cenozoic Granitic and Metamorphic Rocks	--	Gneiss, limestone, schist, and granitic rocks, ranging in age from Mesozoic to Precambrian.

*After California Division of Mines and Geology. Salton Sea (1967) and Santa Ana (1966) Geologic Map Sheets. Does not conform to U.S. Geological Survey stratigraphic nomenclature

From California Department of Water Resources (1970)

FIGURE 5.—Composite stratigraphic section.

area and partly from the adjacent mountain areas. The sediments attain a maximum exposed thickness of 16,500 feet in the southwestern part of Imperial Valley and 18,700 feet in the northwestern part (Dibblee, 1954, p. 21–22). Geophysical evidence (fig. 4) indicates that the fill is probably more than 20,000 feet thick in the center of the basin (Kovach and others, 1962, p. 2864).

In general, earlier studies, as shown by figure 5 (California Dept. Water Resources, 1970), have grouped the basin rocks into three broad categories: (1) A lower sequence of chiefly nonmarine sedimentary rocks of early to middle Tertiary age, but including some volcanic rocks and minor marine sedimentary rocks; (2) a middle marine unit, the Imperial Formation, of late Tertiary (Pliocene?) age; and (3) an upper sequence of mainly nonmarine deposits of late Tertiary and Quaternary age derived primarily from the Colorado River.

The late Tertiary and Quaternary deformation in the Salton Trough is indicated by the configuration of the base of the marine Imperial Formation. In the Chocolate Mountains about 15 miles northeast of Glamis, deposits similar or correlative to the Imperial Formation are exposed at an altitude of about 1,050 feet. However, 22 miles southwest of Glamis in the center of the trough these deposits were not penetrated in an oil test well 13,443 feet deep. Along the west side of the Imperial Valley, the base of the Imperial Formation is exposed at altitudes as great as 1,000 feet above sea level.

The geologic units of the Imperial Valley as shown in the geologic map (fig. 3) have been grouped into four main units. The four units include: (1) The igneous and metamorphic rocks of the surrounding mountains; (2) sedimentary rocks of marine and nonmarine origin of Tertiary age; (3) lakebeds consisting of silt, clay, and some evaporites of Quaternary age; and (4) alluvium consisting of gravel, sand, silt, and clay of Quaternary age.

The Niland Obsidian (Dibblee, 1954) crops out in a row of small domical buttes along the southeastern shore of the Salton Sea. These young knobs of obsidian, scoria, and pumice, with the nearby hot springs, are evidence of geologically recent volcanic activity (Muffler and White, 1969, p. 162).

HYDROLOGIC CHARACTERISTICS OF AQUIFERS

The hydrologic characteristics of the sediments to a depth of about 1,000 feet are known generally from pumping tests of numerous shallow water wells. Water yield and formation permeability of the deeper rocks and deposits are difficult to estimate because few quantitative data were available for examination.

A large area in the central part of the valley contains flowing domestic wells; these extend from 6 miles south of Holtville to several miles north of Calipatria. The Alamo River flows along the western limit of the area of flowing wells. Shallow wells drilled by the Geological Survey show that the area of artesian pressure extends farther west, but west of the Alamo River the pressure is insufficient to cause wells to flow.

An inventory of more than 100 flowing wells, ranging in depth from 350 to 1,300 feet, shows that the discharge ranges from 10 to 100 gallons per minute. Data indicate unfavorable conditions for development of large quantities of usable ground water within the area of flowing wells, and almost the entire central part of Imperial Valley. Aquifer tests at wells about 500 feet deep at Imperial and east of Calexico showed low transmissivity, about 2,000 gpd per ft (gallons per day per foot). Thus, specific capacity of wells may be about 1 gallon per minute per foot of drawndown. (The specific capacity of a well is the yield, in gallons per minute, divided by the drawdown, in feet, from the nonpumping water level in the well.) Ordinarily, wells having specific capacities less than about 10 are considered of marginal value for irrigation use.

A test well drilled to a depth of 560 feet by the Geological Survey on the West Mesa (fig. 16), 8 miles north of Plaster City, was tested. The transmissivity of the aquifer may be about 150,000 gpd per ft.

In the East Mesa area, about 8 miles southeast of Holtville, the Bureau of Reclamation drilled a well (well 92, U.S. Bur. Reclamation 127) to a depth of 1,406 feet on a high heatflow anomaly. Determination of permeability in millidarcies from a sidewall neutron log and a formation density compensated log, in the depth interval 204–1,400 feet, indicated the following:

Depth interval (feet)	Average permeability	
	Millidarcies	Gpd per sq ft
204– 300	743	14
300– 400	1,276	23
400– 500	376	7
500– 600	628	11
600– 700	787	14
700– 800	966	18
800– 900	147	3
900–1,000	610	11
1,000–1,100	937	17
1,100–1,200	654	12
1,200–1,300	537	10
1,300–1,400	651	12
Average	700	13

Multiplying the average permeability value by the well depth gives an aquifer transmissivity of about 18,000 gpd per ft. By comparison, a well drilled 1,000 feet deep at the junction of the All American and Coachella Canals had an aquifer transmissivity about 10 times greater.

A CONCEPTUAL MODEL OF THE SYSTEM

If needed measurements of geologic, hydrologic, and physical parameters were available in great detail and quantity throughout the Salton Trough geothermal basin, it would be a straightforward process to assemble and analyze the data and make the necessary calculations required to estimate usuble and recoverable water in storage. However, this would require knowledge of parameters and boundary conditions and locations and rates of planned production of water. Parameters required would include three-dimensional distributions of temperature, water quality, rock conductivity, permeability, and porosity. Knowing the natural flux of water and heat through the system would also be required, as well as changes in the natural inflow and outflow of water and heat caused by production, if detailed estimates were required.

Making the many necessary measurements of parameters would be extremely costly and very difficult, if not impossible at present. Many parameters would have to be computed, based on indirect measurements of physical, geologic, or hydrologic variables.

Even if the best techniques were used to collect and interpret such a large volume of detailed data, inaccuracies might still reside in the computations of usable and recoverable water in the system. The scarcity and inaccuracy of the existing information plus the fact that most of it is from wells that are not particularly strategically placed for the purpose of making such estimates make the task extremely difficult.

The only recourse is to formulate a conceptual model of the hydrodynamics of the sedimentary basin, considering also the quality and temperature of the contained water. In the remainder of this section of the report the basic concepts and assumptions used in formulating a conceptual model of the Salton Trough hydrothermal system are outlined. On the basis of these assumptions and the model, the few available data for the basin were extrapolated throughout the system as lines of equal temperature, porosity, specific yield, and water quality. Ultimately these lines formed the basis for the estimates of usable and recoverable water derived herein. Thus, assumptions about the basin geometry, its water and heat inflow and outflow, duration of the quasi-steady-state flow system, and many aspects of the water chemistry, all based on very limited data, have critical bearing on the estimates derived.

Undoubtedly the estimates are inaccurate; unfortunately the magnitude of the error cannot be estimated until many additional data are collected.

BASIC CONCEPTS

A hydrothermal system is considered as a heat-transfer mechanism relying for its operation on the transport of water, but not necessarily on a discharge of water at the surface. The system, however, includes at or below the surface a volume of rock and water in which heat flow is greater than in the surrounding area and is probably greater than average. Most of the system, then, consists of a water reservoir in hot rock. Under natural conditions little fluctuation of water level occurs but water is discharged; thus, recharge to the system must also occur.

The basic elements of a hydrothermal system are: (1) A heat source, (2) a recharge mechanism, (3) a circulation (or recirculation) mechanism, and (4) a discharge mechanism.

Prior to this study three presently actively supported conceptual models of the Salton Trough hydrothermal system had been proposed. All three models were formulated in an effort to explain data obtained from wells drilled at the Salton Sea geothermal field. All three models (Berry, 1966; Helgeson, 1968; and White, 1968) were in agreement that the origin of the water in the system was at least substantially if not entirely meteoric. All were in agreement that the source of the heat was almost surely a local magmatic body at relatively shallow depth, but probably at least 7,000 feet below the surface (Griscom and Muffler, 1971).

There were fundamental differences proposed for the water recharge-discharge mechanisms, for the age of the system, and, most importantly, for the source or mode of occurrence of the hypersaline brines produced. There was also disagreement concerning whether or not the source of the meteoric water was the Colorado River or the bordering uplands (Chocolate Mountains). Thus, basic assumptions concerning water source, age of the system, and source of salts led to fundamental differences in the models proposed. Because the conceptual model of the system and its mechanisms have such critical bearing on the interpretations of the limited data available, the choice of the model must strongly influence any estimates of usable and recoverable water in the system. A brief summary of the mechanisms proposed by the three actively supported models may be helpful here.

Berry (1966) depended entirely upon semipermeable membrane filtration of capping shales to increase the total salinity of the water in the reservoir rocks to 155,000 mg/l chloride from an unspecified concentration in the ground water derived from the Colorado River.

Helgeson's model (1968) assumed that thermal evaporative concentration of water derived from the Colorado River occurred during a stage prior to the deposition of the upper 2,500–3,000 feet of predominantly fine-grained sediments of low permeability.

White (1968) actually proposed two slightly different versions of his model; they differed mainly in vapor content of the fluid, mode of discharge, and thermal gradient. We accept White's model as substantially correct and are proposing only a few modifications. One of White's models (1968, fig. 3) is reproduced in figure 6. A slight difference exists between our model (this paper) and that of White, however. White relies on evaporites in the system to supply the salts of the hypersaline brine at the Salton Sea field, whereas ours does not.

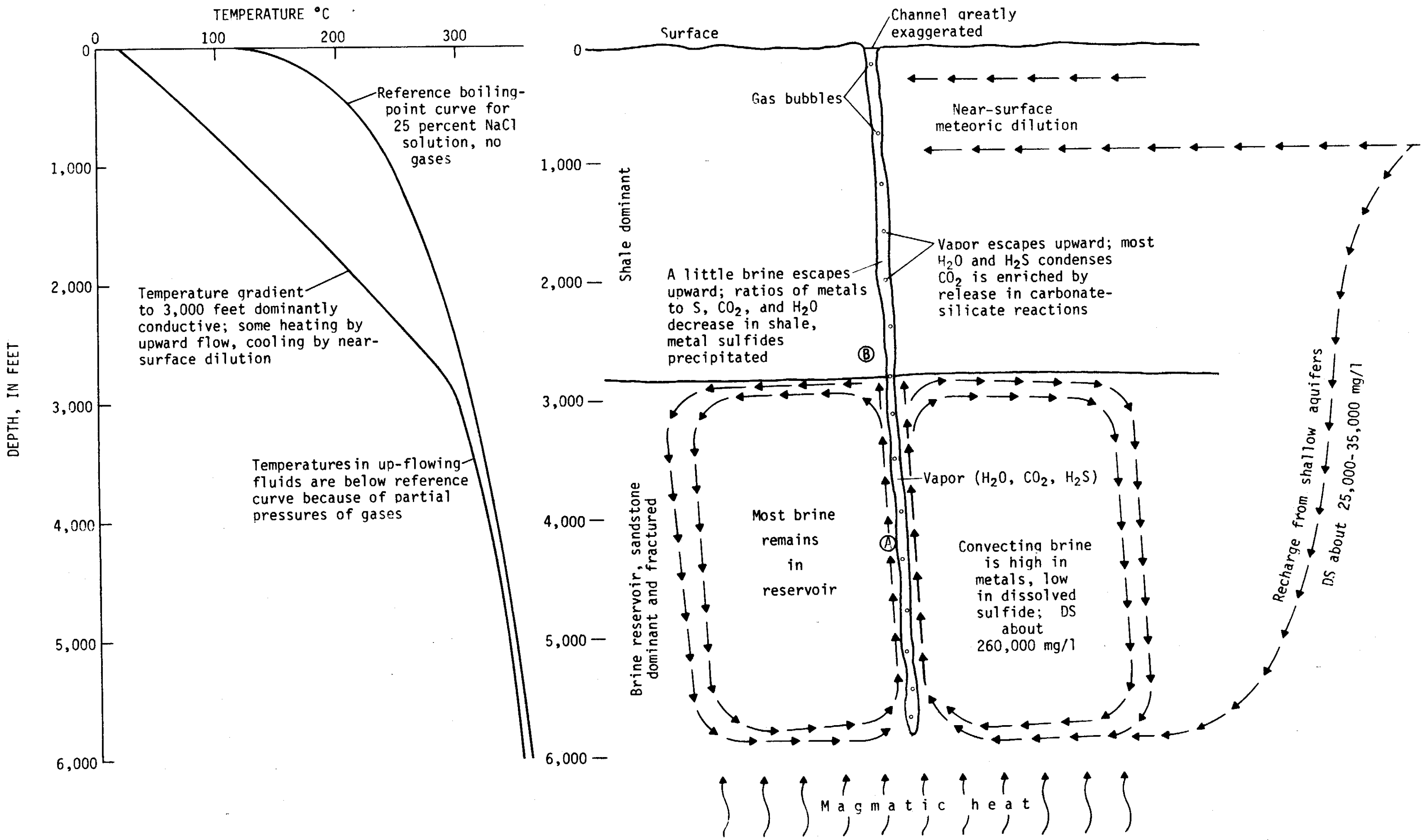
Craig (1969) emphasized the significance of the isotope data and convincingly pointed out weaknesses in Helgeson's model. White (1968, p. 312–318) also presented an excellent analysis of available chemical and isotope data that forms a sound basis for modifying the previous models of Berry (1966) and Helgeson (1968).

SOURCES OF HEAT AND HIGH-TEMPERATURE ANOMALIES

On the basis of seismic refraction and gravity studies by Biehler, Kovach, and Allen (1964), Koenig (1967) estimated that the total crust is only 12–15 miles thick beneath the Salton Sea and is much thinner to the southeast beneath the Gulf of California. The crustal thickness even in the north part of the Salton Trough is considerably thinner than in the bordering mountain areas of the Peninsular and Transverse Ranges (Biehler, 1964).

Heat-flow measurements reported by Rex (1966) are abnormally high in the Salton Sea (Niland) and Cerro Prieto areas but are not unexpectedly high in most of the area. There is, however, considerable variation in the heat-flow pattern within the trough. A pattern of randomly located hotter spots has been observed (Rex, 1970, U.S. Bur. Reclamation, 1971). The known hotter spots are represented as circles in figure 7; the diameters shown are intended to represent only very approximately the size of the anomaly.

Assuming that the heat source lies within uppermost mantle, the 4 miles of water-saturated sediments above the granitic basement provides a near-perfect environment for development of hot-water convection cells. These cells speed the transfer of heat from the granitic-metamorphic basement toward the surface. Where relatively impermeable clay, shale, or other rocks occur, the upward movement of



Model modified after White (1968, fig. 3)

FIGURE 6.—Model for Salton Sea geothermal system, involving a vapor phase.

these heated fluids is impeded. Such confined heat fields may have little or no expression at the surface. However, where major faults cut through the permeable and impermeable layers, heat seeps and other evidences of the convection cell system may show clearly at the surface.

The presence of Quaternary volcanic rocks at Niland and at Cerro Prieto has suggested the possibility of the existence of a magma chamber at a depth greater than 7,000 feet (Elders and Robinson, 1970). The local gravity high at Salton Sea and metamorphism of sediments at Salton Sea and Cerro Prieto are cited as supporting evidence. However, metamorphism was encountered in a deep well (No. 71, 13,443 ft) about 8 miles northwest of Holtville without Quaternary volcanic rocks being present at the surface.

A magnetic anomaly has been mapped in the Salton Sea area (Griscom and Muffler, 1971; Kelley and Soske, 1936). This anomaly corresponds closely to the outcrops of Quaternary volcanic rocks and to the positive gravity anomaly at Salton Sea. This association is considered by some (Griscom and Muffler, 1971; Biehler, 1964; and McNitt, 1963) as evidence of a buried, cooling, magmatic mass that is the source of heat for the geothermal field at Salton Sea.

METAMORPHISM AND CHANGES IN POROSITY AND PERMEABILITY

In places the intense heat is sufficient to cause metamorphism of sediments. White, Anderson, and Grubbs (1963) and Muffler and White (1969) discussed metamorphism of upper Tertiary and Quaternary sediments found in geothermal wells in the Salton Sea area. Evidences of metamorphism of young sediments also are found in wells at Cerro Prieto according to Bernardo Dominguez (Koenig, 1967). The laboratory determinations were made by L. J. P. Muffler, using samples from wells M–3 through M–6 provided by the Commission Federal de Electricidad. Evidences of low-grade metamorphism were found in a deep well (No. 71) near Holtville in the Imperial Valley (Rex, 1966). On the basis of examination of electric logs from other wells, metamorphism is probably common at depth throughout the entire length and breadth of the Salton Trough.

Several workers have suggested that the thick, relatively impermeable shale or clay and volcanic units near the surface of the trough serve as an insulator and thermostat preventing the dissipation of the major part of the geothermal fluid—and therefore the heat—to the surface. At Salton Sea, the shales of the Borrego Formation as used by Koenig (1967), form the impermeable cap. The Borrego Formation becomes increasingly sandy at depth and gradually interfingers with and merges into the Palm Springs Formation (Koenig, 1967). This largely sandstone sequence is the reservoir rock at Salton Sea. Similarly, a metamorphosed argillite cap overlies sandy beds—the reservoir—at Cerro Prieto (Paredes, 1964). Metamorphism may reduce permeability of the shaly cap rock still further.

Estimated average horizontal permeability of the fine-grained deposits dominant in the upper 2,500–3,000 feet at the Salton Sea geothermal field is only 1 gpd per sq ft (gallon per day per square foot); the vertical permeability is probably very much less. Thus the transmissivity may be about 2,500–3,000 gpd per ft.

At the time of deposition, all the sediments consisted of sand, silt, and clay of uniform original mineralogic composition, but under the elevated temperatures and pressures of the geothermal system they are being transformed to low-grade metamorphic rocks of the greenschist facies. Muffler and White (1969) studied these transformations by X-ray, petrographic, and chemical analyses of cuttings and cores from deep wells that penetrate the sedimentary section. They reported, simply stated, that the reactions are:

$$\text{montmorillonite} \rightarrow \text{illite}$$
$$T < 100°\text{C}$$
$$\text{illite-montmorillonite} \rightarrow \text{K-mica}$$
$$T < 210°\text{C}$$
$$\text{dolomite} + \text{ankerite} + \text{kaolinite} + Fe^{+2} \rightarrow \text{chlorite} + \text{calcite} + CO_2$$
$$T = 125°\text{C to} < 180°\text{C}$$
$$\text{calcite} + \text{silicates} \rightarrow \text{epidote} + CO_2$$
$$T > 290°\text{C}$$

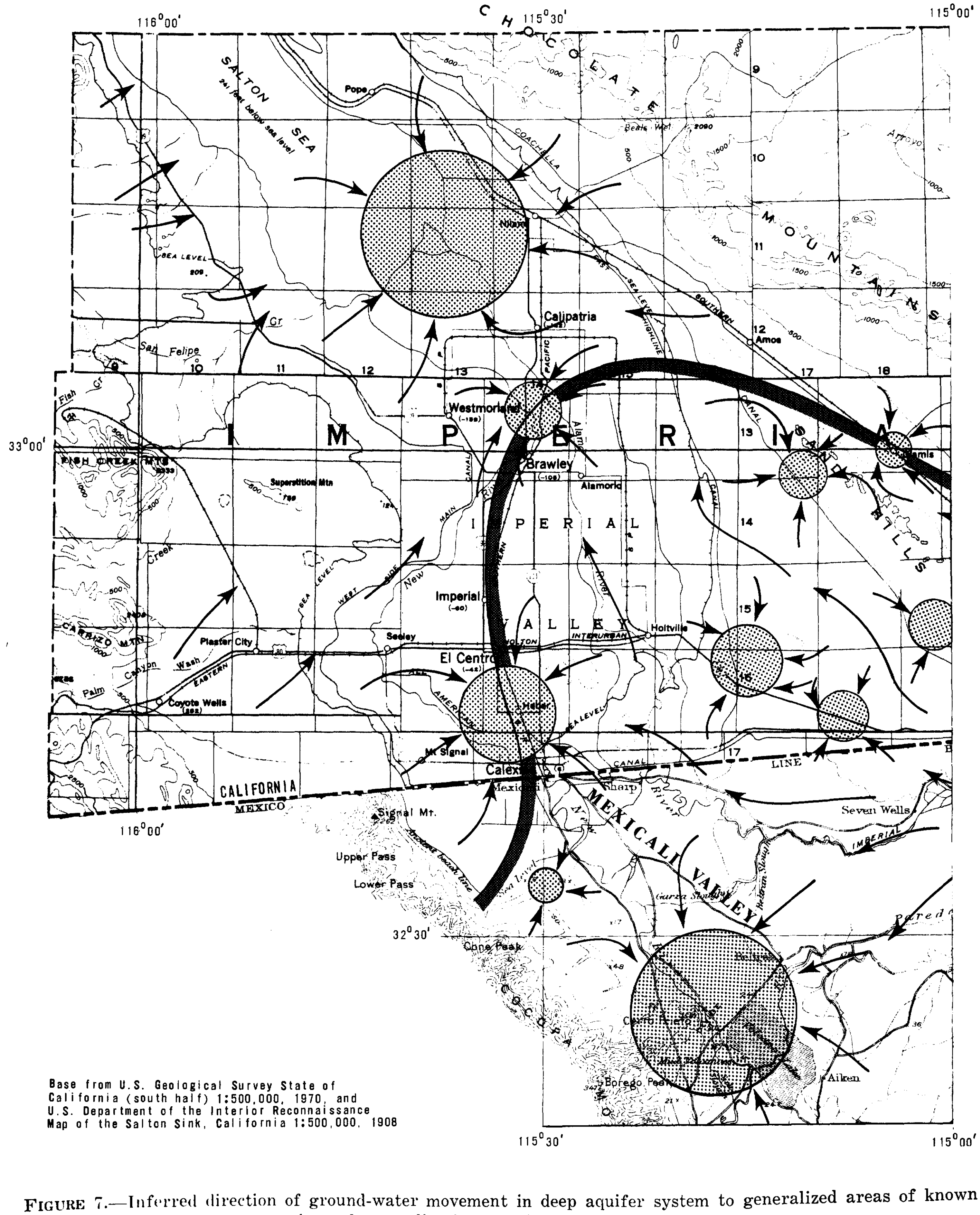
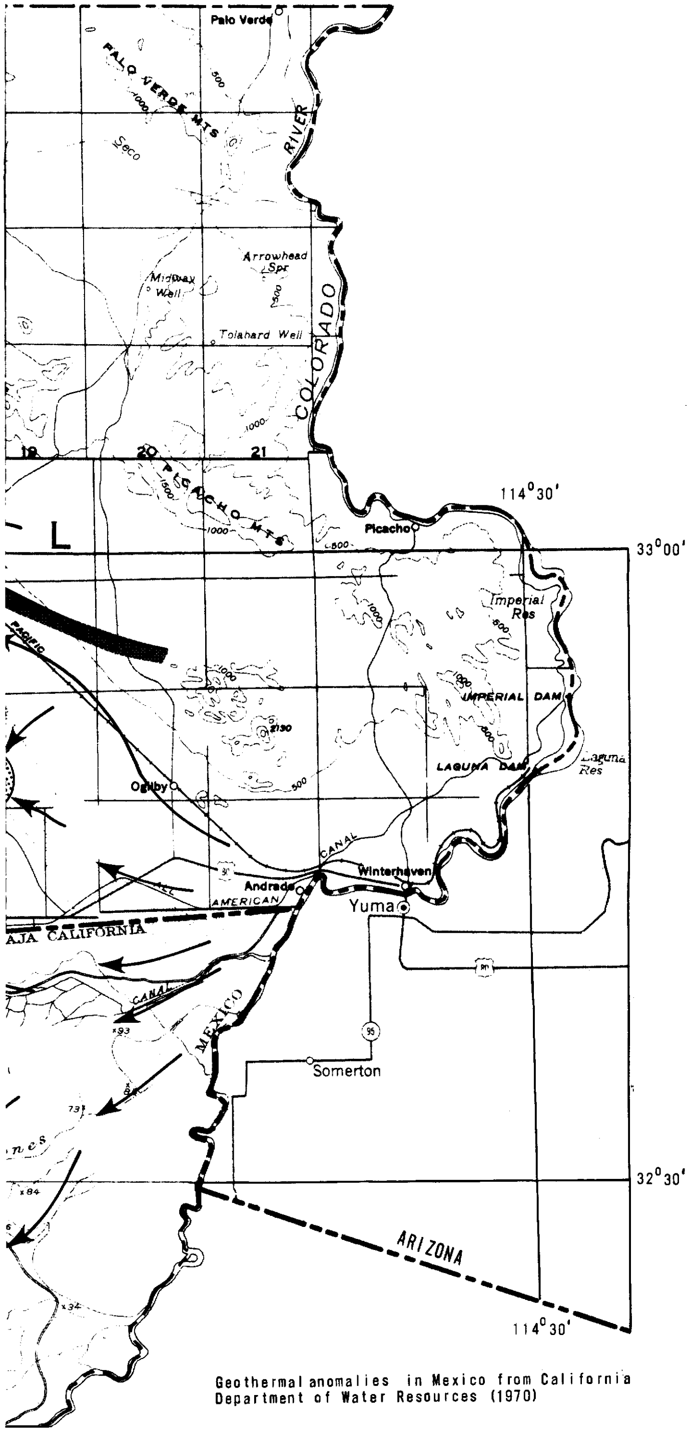


FIGURE 7.—Inferred direction of ground-water movement in deep aquifer system to generalized areas of known geothermal anomalies in Imperial and Mexicali Valleys.



EXPLANATION

Known geothermal anomalies

Direction of ground-water movement in deep aquifer system

Line dividing source of water derived from local mountains and water derived from Colorado River area

TRUE NORTH

MAGNETIC NORTH

$14\frac{1}{2}°$

APPROXIMATE MEAN DECLINATION 1971

0 5 10 15 20 MILES

CONTOUR INTERVAL 50 AND 500 FEET
DATUM IS MEAN SEA LEVEL
Elevations and topography in Mexico are approximate

FIGURE 7.—Continued.

The compositions of the sediments presently undergoing metamorphism in the Salton Sea area show a marked decrease in carbon dioxide with depth.

On the basis of these findings and examination of drillers' logs, electric logs, gamma-ray logs, and neutron logs of wells, where temperatures exceed about 250°C most of the original interstitial sediment permeability has probably been greatly reduced or entirely eliminated. Fractures have formed extensively and may now account for virtually all available permeability. Even at shallower depth and where temperatures are lower than 250°C but greater than 100°C, significant changes in permeability presumably have accompanied metamorphism.

On the basis of available data, estimates of average permeability cannot be derived for the deposits deeper than about 3,000 feet. Deep wells at Salton Sea and Cerro Prieto, however, individually yield up to 200 or more tons per hour of steam and water—a quantity great enough to make production of water and steam economically feasible if technical problems can be overcome.

High temperatures and pressures that caused metamorphism and resulted in reduced natural permeability of the rocks have also contributed to reduced porosity. Presumably, porosity has been reduced mainly through compaction of the sediments due to continuous deposition from the Colorado River. Porosity may also be substantially reduced locally near the margins of deep convection cells by cementation of the rocks and deposits with calcium carbonate, calcium sulfate, and perhaps silica carried toward the cells by recharge water. For estimates on the assumed average porosity of the deposits see the section "Estimated Porosity and Specific Yield of the Rocks and Deposits."

AGE OR DURATION OF THE STEADY-STATE FLOW SYSTEM

Near the Salton Sea geothermal field five domes of pumiceous rhyolite of late Quaternary age are exposed. The surface volcanic rocks have a probable age of 16,000 years as determined by potassium-argon dating (Muffler and White, 1969, p. 162), but that age may be in error by as much as 40,000 years. This certainly does not provide a precise age for the steady-state flow system, but it does suggest that the intense heat anomaly at the Salton Sea hydrothermal field is probably related to volcanism not older than about 55,000 years.

The deuterium content of the brine (White, 1968, table 1) is nearly identical with that of the overlying saline springs in the area and spring water from the Chocolate Mountains. The deuterium content is unlike that of ocean water, marine connate water, and water from the present Colorado River or the Salton Sea. Thus, only water from the bordering Chocolate Mountains can be the source of water in the deep brine reservoir.

Helgeson (1968) considered that 12 sq mi (square miles) (30 km^2 (square kilometers)) have been proved by drilling to contain hypersaline high-temperature brine at the Salton Sea field. However, White (1968) considered this estimate conservative and that the brine probably underlies about 20 sq mi (50 km^2). Additional data are not available and White's estimate is still considered the best available of the size of the area underlain by the hypersaline brine reservoir.

Available data indicate a probable average effective porosity of about 10 percent in the rocks of the brine reservoir. If the rocks containing the high-temperature brine in the convecting system (fig. 8) are assumed to be about 50 km^2 in area, 1 km thick, and the porosity is 10 percent, the 50 km^3 (cubic kilometers) of rock then contains 5 km^3 of brine.

White (1968) computed that 50 km^3 of meteroric water containing $\delta O^{18} \approx -11$ per mil (similar to that from the nearby Chocolate Mountains) would be the total flow necessary through the rock to convert the 50 km^3 of delta sediments originally containing $\delta O^{18} \approx +18$ per mil to the present observed O^{18} values of the reservoir rocks, or $\delta O^{18} \approx +8$ per mil.

White (1968) also estimated the rate of discharge and recharge to the brine reservoir at about 500 gpm (gallons per minute) or 30 lps (liters per second). This was based on 50 km^3 of meteoric water flowing through the brine reservoir during a total assumed time of 50,000 years.

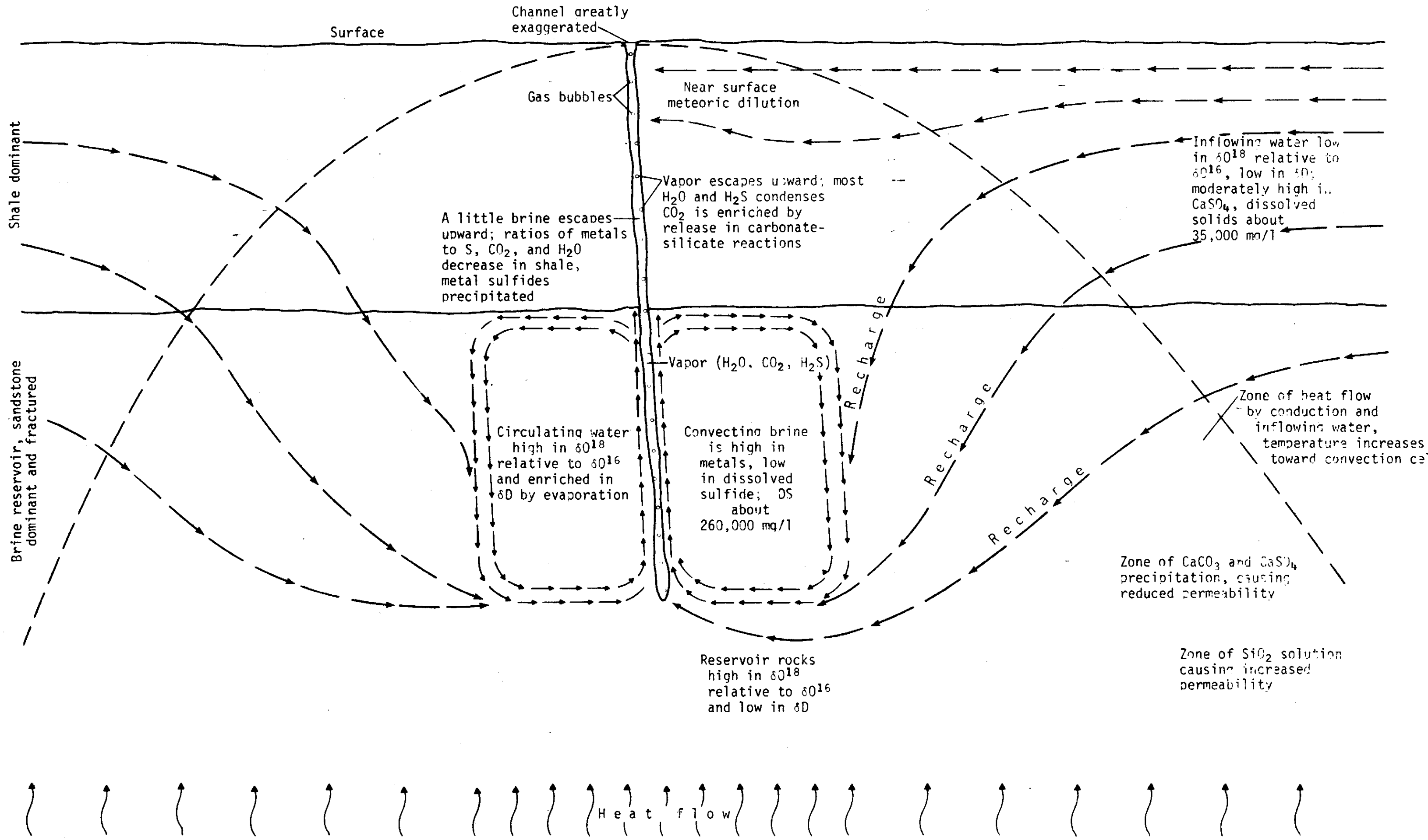


FIGURE 8.—Modified model for Salton Sea geothermal system, showing source of recharge and water-quality changes.

Thus, one possible estimate of age or duration of the steady-state flow system is 50,000 years. Because of the great possibility of errors in estimating reservior depth and area, rock porosity, and chemistry of water recharging the brine reservoir, the duration of the flow through the system can be varied. For example, if the reservoir area is larger, if it is deeper, or if the rock is more porous, either the rate of recharge would be greater or the duration of flow longer. Although buried volcanic rock presumably could be older than 50,000 years, it seems unlikely that the estimate of reservoir size is too conservative. We arrive at this conclusion because the recharge rate (500 gpm) seems to us to be about the right magnitude for the region. On the other hand, that rate of recharge is about the maximum that could reasonably be expected from the Chocolate Mountains during the 50,000-year period. During late Pleistocene time the average rainfall and runoff presumably were greater than those under present conditions, and the greater recharge presumably was sufficient to supply an average of about 500 gpm for the entire period, even though the area now has a very low average rainfall and runoff, and presumably supplies less than 500 gpm recharge.

If the area of the reservoir is smaller or it is shallower, or if the rock is less porous, the rate of recharge would be smaller or the duration of flow shorter. Data are not available to provide a basis for selection among possible alternatives. On the basis of all the evidence now at hand we favor the possibility of a somewhat smaller brine reservoir, a somewhat shorter duration of flow in the system, and a somewhat smaller rate of recharge.

GEOTHERMAL GRADIENTS

A large number of measurements of fluid and rock temperatures have been made in wells in the Imperial Valley area. Even so, many reported measurements are probably grossly in error. Because of the paucity of data from deep wells, temerature data from shallow wells were extrapolated downward. This was necessary to estimate the three-dimensional distribution of temperature throughout the system; temperature was the only widely available information that could be used as an index of the degree of metamorphism of the rocks. Because the degree of metamorphism strongly influences the rock porosity and permeability, temprature was also used as an index of the probable total porosity and the percentage of the contained water that might be producible—that is, recoverable by wells. We assumed that if sufficient change in hydraulic pressure (or head) is imposed during production, water yielded from the rocks and deposits will exceed the specific yield and approach the porosity where temperature is greater than 100°C.

Many temperature data are recorded on electric logs of wells. Many of these data, however, do not represent formation rock temperature. In some cases, reliance was placed in the recorded bottom-hole temperatures, if other more accurate measurements were unavailable. Errors in the data also result from flow of drilling fluid in test holes, water flow in the rocks or wells, salinity of the fluids, and, of course, instrument malfunctions caused by the high pressure and temperature commonly encountered. The overall problem of obtaining representative and reliable depth-temperature curves for wells in the Salton Trough area has been illustrated by many authors (Clayton and others, 1968, p. 973; McNitt, 1963, fig. 15). Data from a typical well at Cerro Prieto, Mexico, are used by the U.S. Bureau of Reclamation (1971, fig. 2) to illustrate the problem of obtaining meaningful temperature data from test wells.

Bullard (1947) and Jaeger (1956) found that once a test hole is drilled it takes about 20 times the time taken to drill the test hole for thermal equilibrium to be reestablished. However, spot temperatures can be used before they return to equilibrium if temperatures at several depths are measured at intervals after drilling is stopped. The drilling period is very short, of course, if temperatures are measured near the bottom after drilling stops. According to Lachenbruch and Brewer (1959) the equilibrium temperature $T(\infty)$ can then be determined for any given depth z from the equation

$$T(t)-T(\infty)=C\ \ln(1+t_1/t_2),$$

where $T(t)$ is the temperature observed at the time t_2 after drilling stopped,

t_1 is the time between when the drill reached depth z and the time drilling stopped,

and C is a constant which depends on the diameter of the hole, the temperature, the depth, and the temperatures and thermal properties of the fluid and surrounding rock.

Errors in the extrapolations can also result from unknown variations: (1) In the thermal conductivity of the rocks (McBirney, 1963); (2) from uncorrected effects due to water movement (Jaeger and Sass, 1963); (3) unknown intrusions of volcanic rocks or other sources of high-heat flow (Griscom and Muffler, 1971); (4) the effects of changing surface conditions in one area or time as compared to another (Lachenbruch, 1957); and (5) the effects of nearby topography and rock types (Jaeger and Sass, 1963; Jeffrys, 1940; and Bullard, 1940).

Needless to say, available temperature data for the Salton Sea hydrothermal system were not corrected for the above-listed effects. Available time, accuracy of the basic data, and desired accuracy of the estimates of recoverable water did not warrant that such corrections even be attempted.

Despite all the questions about reliability of the temperature measurements and the many possible sources of errors that can be introduced when extrapolating shallow temperatures downward to great depth, such extrapolations had to be made in order to estimate recoverable and usable water in storage in the basin. The geothermal gradient, $\partial T/\partial z$, is the rate of increase of temperature with depth. In the Imperial Valley area the heat flux toward the surface ($q=K\ (\partial T/\partial z)$) is areally variable, and the largest sources of errors in the temperature-depth extrapolations probably have occurred because data are lacking to determine one or another of the three following variables:

1. The thermal conductivity of the rocks and water throughout the system.
2. The mechanism of the heat flux: Whether the heat flows through the rock and water mainly by conduction or mainly by convection of water.
3. The rate of heat flux toward the surface: In some areas high heat flux may remain undetected and the geothermal gradients may be considerably different than those extrapolated (figs. 9, 10, and 11).

Item 1, above, causes the geothermal gradient to vary vertically in zones where heat flows dominantly by conduction. Item 2, above, can also cause the geothermal gradient to vary vertically in the rocks. The depth-temperature variations were heat flux is dominantly by convection and where it is dominantly by conduction are discussed in the following sections of this report.

The criteria for distinguishing conductive and convective regimes from the temperature data were as follows:

1. Conductive: Uniform gradient (allowing for conductivity increases with depth) that extrapolates to a (meterologically) reasonable mean surface temperature.
2. Convective: High temperatures with small gradients that extrapolate to high surface temperatures.

On the basis of these criteria and available temperature data we assumed that heat flow in the entire Salton Trough is mainly conductive except at the two hydrothermal fields (where it was observed to be otherwise).

Our preliminary interpretation of the temperature-depth relations along sections *A–A′*, *B–B′*, and *C–C′* (fig. 2) is shown in figures 9, 10, and 11. Areas where Rex (1970) computed variations in the geothermal gradients in Imperial Valley are shown in map 1215–300–3 (U.S. Bur Reclamation, 1971). In some areas the temperature-depth relations shown in figures 9, 10, and 11 are somewhat different from geothermal gradients obtained by Rex (1970) by measuring temperatures in very shallow wells. The differences arise mainly from assumptions about the physical properties of the rocks, water chemistry, and heat flux used to extrapolate the temperature data to much greater depth.

HEAT FLOW BY CONDUCTION

In the entire Salton Trough hydrothermal system, except in the hot spots of high-temperature anomalies and in the Salton Sea and Cerro Prieto hydrothermal fields, heat flux to the surface is probably mainly by conduction from about 3,000 and 2,400 feet, respectively.

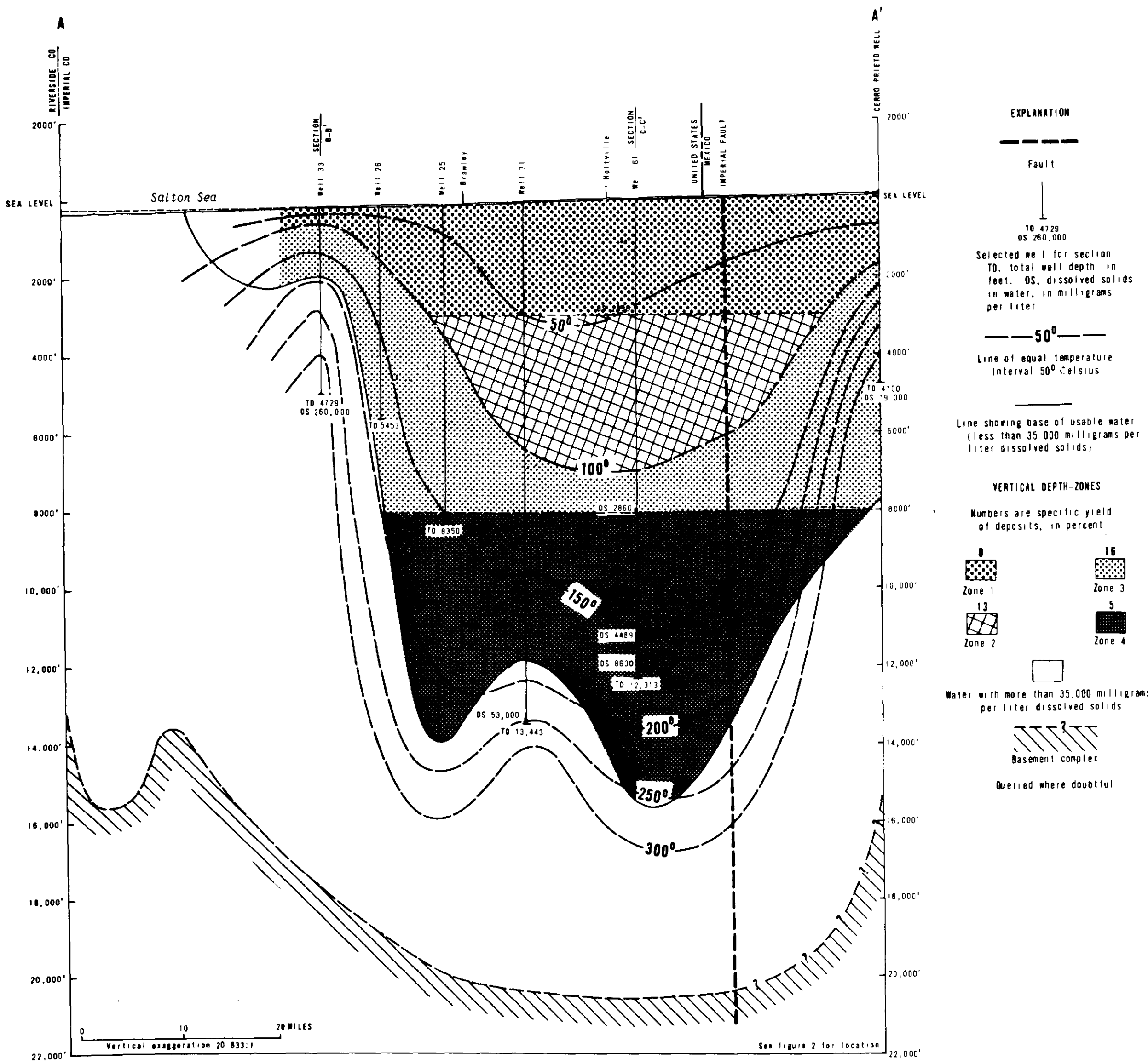


FIGURE 9.—Hydrologic section *A–A'*.

At the Salton Sea hydrothermal field, the geothermal gradient in zone 1 (in the deposits extending to a depth of about 3,000 ft below the surface) averages nearly 10°C per 100 feet (fig. 6). In that entire zone heat flux is probably dominated by conduction. At depths greater than 3,000 feet heat flux is probably dominated by convection. At Cerro Prieto the geothermal gradient in zone 1 (the deposits extending to about 2,400 ft below the surface) also averages about 10°C per 100 feet and heat flow is also probably dominated by conduction in those deposits; at depths greater than 2,400 feet heat flow is probably dominated by convection.

At well 85 (U.S. Bur. Reclamation well 116) southeast of Holtville the average geothermal gradient in zone 1 (only 1,400 ft tested) averages about 7°C per 100 feet, in a zone where conduction presumably dominates.

In the areas outside the known hot spots, in most of the system, all available data indicate that in zones having heat flux probably dominated by conduction, geothermal gradients range from less than 1°C per 100 feet across some thick zones to as much as 2° or 3°C per

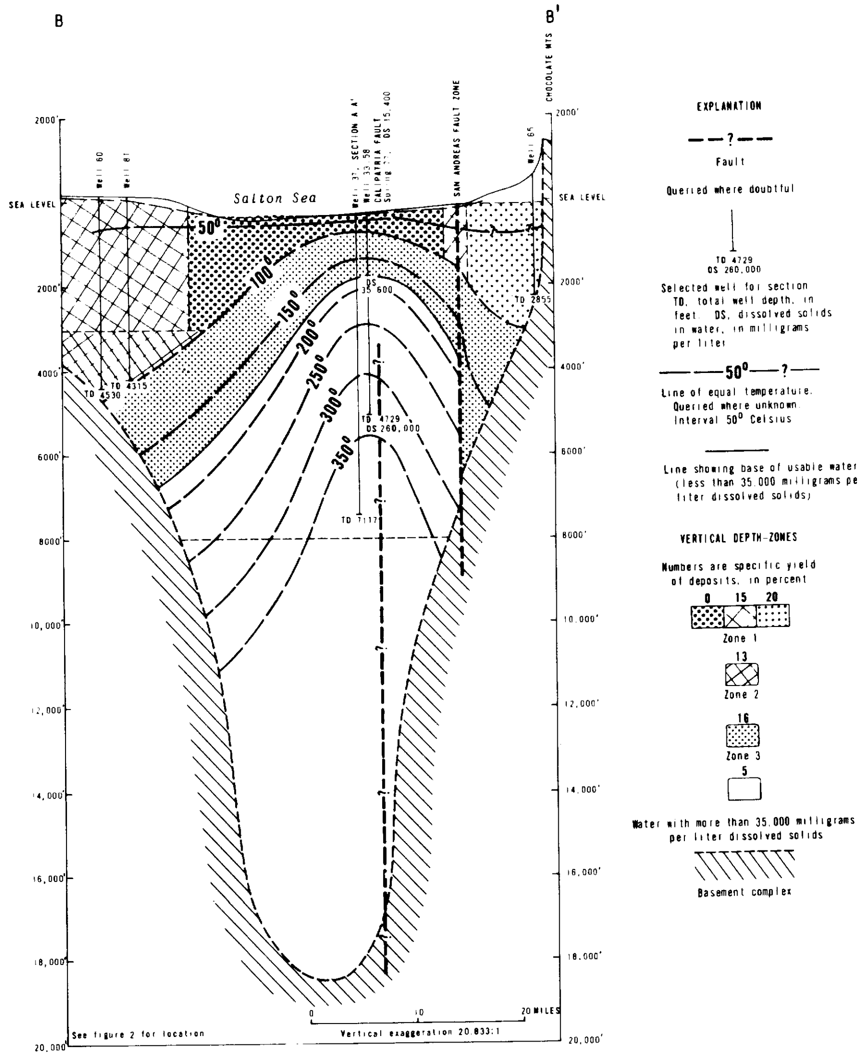


FIGURE 10.—Hydrologic section *B–B'*.

100 feet across other thick parts of the total sedimentary section (figs. 9, 10, and 11).

HEAT FLOW IN WATER CONVECTION CELLS

Within the deeper parts of the Salton Sea and Cerro Prieto hydrothermal systems, heat flux is probably dominantly by convection. In a circulation system where downflowing water recharging a deep convection cell is dilute and relatively low in temperature, and upflowing water is a hot, 25 percent sodium chloride solution, the temperature of the brine must be about 200°C higher than the dilute water for convective circulation to occur, according to data determined by L. J. P. Muffler and reported by White (1968, table 2). For this reason we believe it is impossible to predict on the basis of available temperature and chemical data whether or not deep convective cells remain undiscovered in the Salton Trough area outside the known hydrothermal fields at Salton Sea, Calif., and Cerro Prieto, Mexico. Near deep well 71, however, northwest of Holtville, there are a few temperature measurements available for examination; these and water-quality data indicate that the temperature and water quality from near the bottom of the well exhibit a sufficiently great contrast when compared with data from only slightly shallower depth, that a deep convection cell may exist at

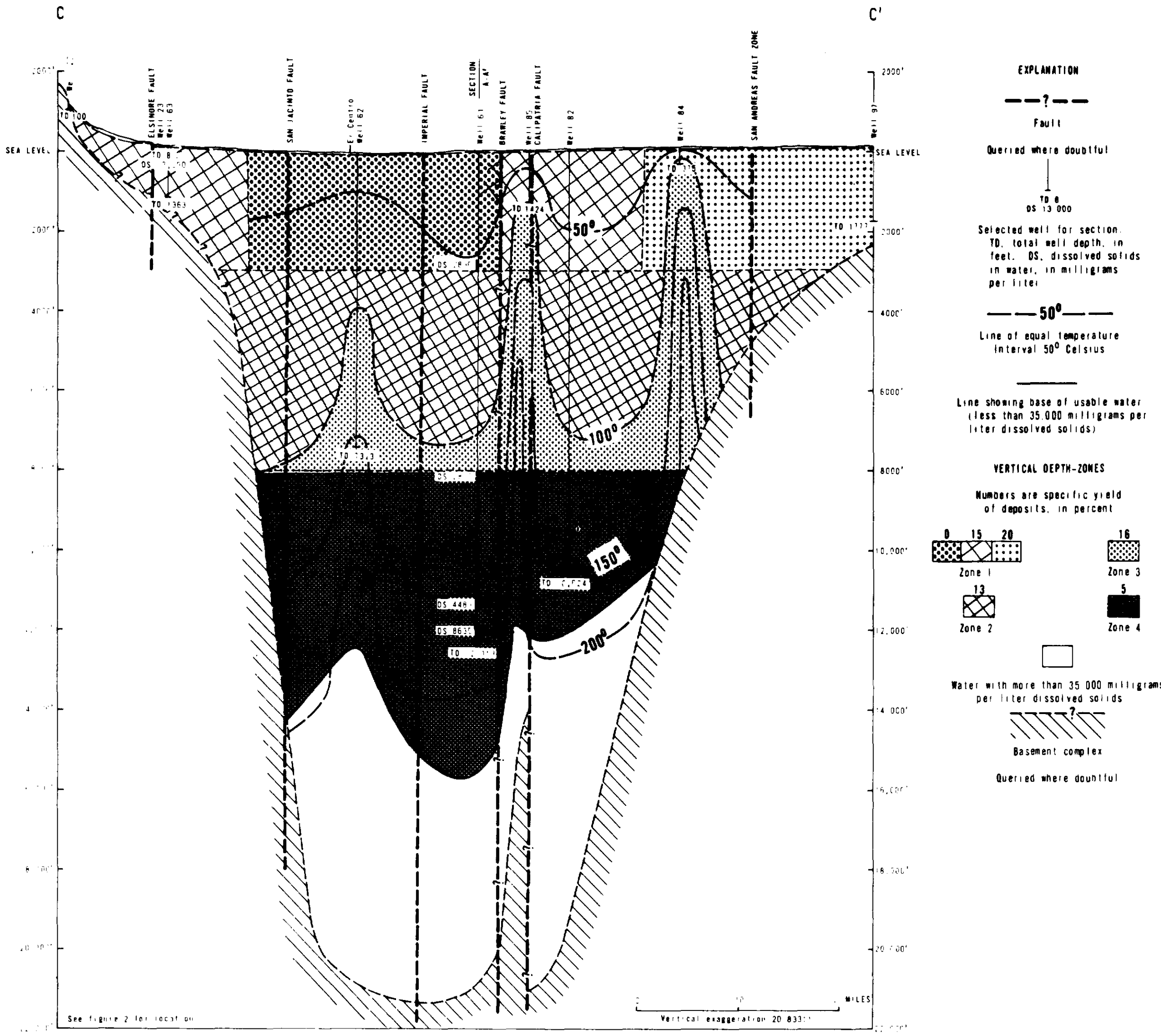


FIGURE 11.—Hydrologic section C–C'.

a depth only slightly greater than that reached by the drill.

At well 61, southeast of Holtville, a deep convection cell probably exists at a depth several thousand feet deeper than that reached by the drill.

Within the convection cells at the Salton Sea and Cerro Prieto fields, the temperature gradients are much lower than where the heat flux is dominantly by conduction (fig. 6). Presumably the temperatures of the upflowing fluids throughout the cell are only slightly below the reference boiling-point curve for the brine solution analyzed. The temperature is slightly below the reference curve probably because of partial pressures of gasses in the system (fig. 6).

THE DYNAMIC SYSTEM

Most basic elements and mechanisms of the Imperial Valley area hydrothermal system cannot yet be measured directly. A satisfactory conceptual model of the system must represent the mechanisms and elements of the prototype, insofar as the available data permit the system to be understood. The mechanisms proposed for the system must be compatible not only with available data but also with principles of chemistry and physics.

The model proposed must provide for operation of a system in which the following elements are known or assumed:

1. The recharge and discharge mechanism.
2. The source of the recharge water.
3. The average rate of long-term recharge.
4. The manner, rate, and location of discharge.
5. The chemical quality of recharge and discharge.
6. The spatial variation in water chemistry throughout the system.
7. The size of the reservoir.
8. Changes caused in the system by the flux of heat, water, gas and vapor, and chemicals.
9. The distribution of water, gas, and vapor, and rock temperature, porosity, an permeability.
10. The age of the system or the duration of the quasi-steady state of flow.

Thus rates of water flow in the system are very important. Because rates of recharge and discharge have not been measured, and these still cannot be measured directly, they must be computed indirectly for purposes of formulating the model. The only practical means of computing recharge and discharge is by estimating the size of the reservoir, the chemistry of the inflowing water, the assumed and observed induced changes in water chemistry in the reservoir, the chemistry of the discharge water, and the length of time the system has operated.

Explaining the observed data by using a simple model applicable to the entire Salton Trough hydrothermal system is desirable. On the basis of the data available, it seems that this is possible. For example, Koenig (1967) showed that although the concentration of salts is much greater at Salton Sea than at Cerro Prieto (table 1) there is remarkable agreement in the ratios of ionic concentration at both sites.

Therefore, it is important to formulate one model for the whole hydrothermal system and

TABLE 1.—*Analysis of water from geothermal wells at Niland, Cerro Prieto, and Arizona, in milligrams per liter*

Element	Niland			Cerro Prieto	Arizona
	Well 39 (White, 1968, table 1, analysis 2)	Well 36 (Helgeson, 1967b)	Well 57 (California Dept. Water Resources, 1970)	M-3 (Alonso Espinosa and Mooser, 1964)	Musgrove 1 (Olmsted and others, 1972)
Sodium	50,400	53,000	10,600	5,610	[1]141
Potassium	17,500	16,500	1,250	1,040	—
Calcium	28,000	27,800	1,130	320	148
Lithium	215	210	40	14	—
Magnesium	54	10	74	(2)	43
Strontium	400	440	85	27	—
Barium	235	250	3	57	—
Rubidium	135	70	—	(2)	—
Cesium	14	20	—	(2)	—
Iron	2,290	2,000	.7	(2)	—
Manganese	1,400	1,370	6.4	(2)	—
Lead	102	80	—	(2)	—
Zinc	540	500	—	(2)	—
Silver	(2)	(2)	—	.05	—
Copper	8	(2)	—	.09	—
Silica	400	400	120	(2)	18
Chloride	155,000	155,000	19,700	9,694	188
Boron	390	390	100	[3]12	—
Fluoride	15	(2)	1	.88	—
Sum of sulfur	(2)	30	—	≈10	—
Dissolved solids	258,973	259,000	34,800	≈17,000	1,000

[1] Includes potassium.
[2] Not reported.
[3] Recalculated from H_3BO_3.

important to determine the duration of time during which the system has operated at an assumed steady state.

MECHANISM OF RECHARGE AND DISCHARGE

The model first proposed by White (1968) and reproduced herein (fig. 6) has been modified somewhat in figure 8 to show our concept of the Salton Sea (or Cerro Prieto) hydrothermal field as an evaporative convective system. In this model some precipitation falling on the local mountains east of the basin (Chocolate Mountains) becomes ground-water recharge near the basin margin. All the ground water flows toward the Salton Sea but some descends to a depth greater than 6,000 feet beneath the surface in the Niland area. As the water flows west and descends to depth, the content of dissolved solids increases, presumably through redissolution of salts contained in the fine-grained deposits accumulated in this area of long-continuing evaporation near the lowest part of the valley. No evaporites (as distinct beds) have been found in any drill holes, but there is appreciable anhydrite (probably initially gypsum) in drill cores (Muffler and White, 1969). At the surface there were extensive evaporites prior to 1906. Furthermore, the geologic history of the northern part of the Colorado River delta throughout the late Tertiary and Quaternary was probably alternating flooding and evaporation (Muffler and Doe, 1968; Sykes, 1937a, b). Evaporites are difficult to recover in drill cuttings. Even though their detection is difficult, evaporites probably exist at depth, particularly in the upper 3,000 feet of the sediments. Water near the base of the shale-dominant zone near the Salton Sea field probably contains 25,000–35,000 mg/l dissolved solids (see well 57, table 1).

Some of the water moves down in response to the greater hydrostatic pressure outside than inside the convection cell, to eventually recharge the deep system.

The descending water is relatively low in δO^{18} and δD, and moderately high in calcium sulfate. Because the Colorado River delta deposits were originally high in δO^{18}, a disequilibrium exists, hence the O^{18} shift observed by Craig (1966) and Clayton, Muffler, and White (1968). The deuterium content of the brine proves its Chocolate Mountains source. Presumably some precipitation of calcium sulfate and calcium carbonate takes place because of heating of the descending water as it intercepts heat flowing toward the surface by conduction. The abundance of carbon dioxide, a product of the metamorphism taking place at depth, may affect the calcium carbonate solubility to an even greater extent than the increased temperature.

Upon entering the convecting system the water rises; some is eventually evaporated, and vapor and gas escape upward. Carbon dioxide, ammonia, boron, and hydrogen sulfide are enriched as explained by White (1968) and Barnes (1970). The salts remain in the reservoir and are progressively concentrated. As explained previously, this mechanism presumably persisted during a period calculated to be not longer than 50,000 years, but probably more than 25,000 years.

QUALITY AND QUANTITY OF WATER AND CONCENTRATION OF SALTS

Assuming that the brine reservoir at the Salton Sea field is in a maximum rock volume of about 50 km^3, that this has an average 10 percent porosity, and that the recharge has been 50 km^3 during 50,000 years, the average recharge rate is about 500 gpm (30 lps) or about 800 acre-feet per year. This is somewhat larger than would be expected using historic rainfall-runoff relations from the Chocolate Mountains, but very probably was considerably less than the available recharge during the late Pleistocene and Holocene fluvial periods which contributed water to large perennial lakes in the basin (Hubbs and others, 1963). Runoff in the Colorado River, of course, was the principal source of the lake water.

Our concept of the water recharge-discharge relations for the shallow and deep aquifer systems and the water-quality changes within the system are schematically shown in figure 12. This pipe model for the Salton Trough fresh-water and hydrothermal system indicates our concept that both the Salton Sea and Cerro Prieto deep convection systems have a common mechanism and mode of origin. The only substantial difference in the two systems is the

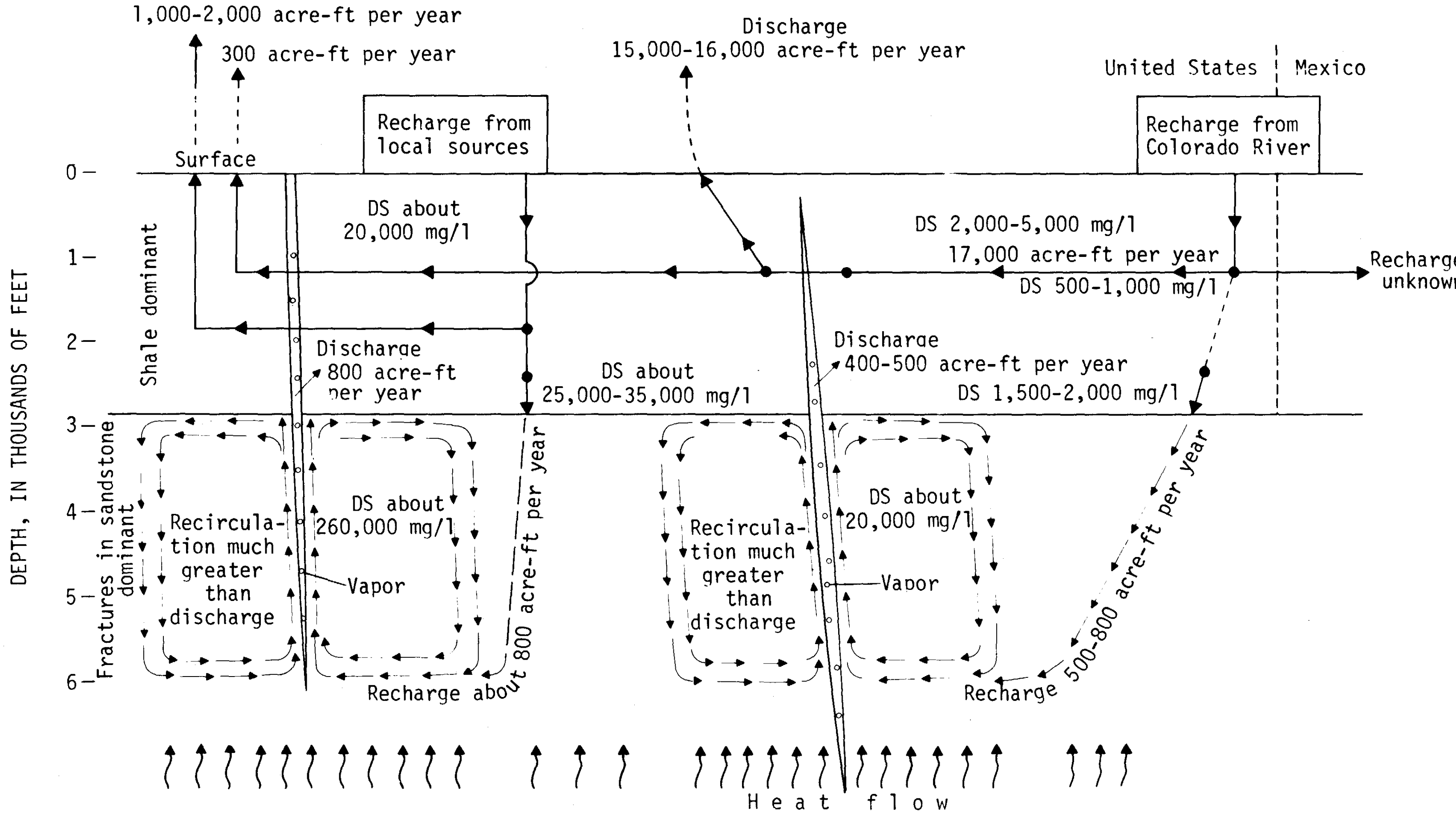


FIGURE 12.—Schema for a pipe model for water and dissolved solids input-output of the Salton Trough hydrothermal system.

quality of the recharge water, which is much less saline at Cerro Prieto.

The total ground-water recharge to the Imperial Valley area from the Colorado River under natural conditions was probably about 17,000 acre-feet annually (O. J. Loeltz, U.S. Geol. Survey, written commun., 1971). This 17,000 acre-feet does not include the unestimated recharge presently occurring as a result of losses from irrigation canals and from irrigated land. The recharge estimate is based on data from the water-level contour map (fig. 13) showing the hydraulic gradient and width of the aquifer in the area of ground-water recharge in the southeast part of the valley and an estimated aquifer transmissivity of about 500,000 gpd per ft in the recharge area.

Only a small part of the recharge reaches the Salton Sea as continuous flow in the aquifers. We estimate this flow to be 300 acre-feet per year, on the basis of the water-level contour map (fig. 13) and an estimated transmissivity of 3,000 gpd per ft for the deposits containing water probably derived from the Colorado River in the area of inflow to the sea. The remainder of the recharge, 16,700 acre-feet per year by subtraction, discharges directly or indirectly by upward flow to either the land surface, the river channels, or the drainage-tile network widespread in the irrigated area. Part of this discharge may follow a very indirect route. A small part may descend to great depth to recharge deep undiscovered convection cells in the hydrothermal system to rise again, leaving most of its dissolved salts behind, to eventually rejoin water in the upper zones and ultimately reach the surface to evaporate, be transpired by plants, or to enter some part of the surface-drainage system.

Under very long term average conditions, recharge to ground water in the Imperial Valley area from local sources may have averaged about 3,000–4,000 acre-feet annually. Under present conditions of rainfall and runoff, the average annual recharge from local sources is probably considerably less; it may even be less than half the very long term average, or about 1,500 acre-feet per year. Discharge occurs as direct inflow to the Salton Sea, by evapotranspiration where the water table is shallow, and presumably in small part to local drains and the river channels in the area of irrigated land.

Recharge to the deep aquifers is by ground-water inflow from the shallow aquifers, presumably mainly near the basin margins, but probably also by descending flow near the deep, hot convecting cells. The recharge and discharge to the deep convecting cells, both at Salton Sea and Cerro Prieto, are estimated to average 500 gpm (30 lps).

RELATION OF SALINITY OF RECHARGE AND DEEP BRINE

During the 25,000–50,000 years that the mechanisms of the hydrothermal system are presumed to have operated, about 50 km^3 of recharge water originating in the overlying zone from 1,500 to 3,000 feet and presumably containing about 25,000–35,000 mg/l dissolved solids (see well 57, table 1) probably has flowed into the deep convection cell at Salton Sea. The discharge has been virtually salt-free flow in the vapor phase. Thus, during that time the salinity of the deep brine has increased to about 260,000 mg/l.

At Cerro Prieto, using the same age, volume of rock and porosity, and recharge and discharge, the deep brine salinity has increased to only about 15,000–20,000 mg/l, because the dissolved-solids content of the recharge water originating in the overlying 2,400-foot zone presumably has averaged only about 1,500–2,000 mg/l. In this area evaporites, as distinct beds or nodules in the sediments, could not be expected because the area south of the delta axis has not been within a closed basin.

On the basis of the model proposed and an assumed uniform duration of high heat flow in all the hot anomalies, we postulate that the dissolved-solids content of water in all deep convection systems yet to be discovered may exceed 35,000 mg/l wherever the concentration of dissolved solids in the recharge water from the overlying deposits is greater than 4,000–5,000 mg/l.

ESTIMATED POROSITY AND SPECIFIC YIELD OF THE ROCKS AND DEPOSITS

AVAILABLE DATA

Factual data for determining porosity and specific yield of the rocks and deposits derived from geophysical logs are lacking in most of Imperial Valley. The most common geophysical logs available are electric logs from several oil-test and geothermal wells. These logs are not suited to the needs in calculating formation porosity unless supporting information is available. More useful logs for this purpose include sonic, formation density, neutron porosity, and the gamma ray-neutron. Inspection of the available log data revealed five logs from four wells that were particularly useful for porosity evaluation. These wells are shown below.

Location No.	Name	Type of log	Well depth (feet)	Log interval (feet)	Date logged
39	Geothermal Inc.-IID 1	Gamma ray-neutron	6,141	64–1,700	1962
71	Standard Oil-Wilson 1	Sonic	13,443	99–9,484	1963
82	American Petrofina	Sonic	10,624	1,530–7,988	1966
92	Bureau of Reclamation 127	Formation density and neutron porosity	1,406	204–1,400	1971

In the deep wells, drilled years ago, the logged interval does not reach the bottom of the wells. The formation temperatures encountered during the deeper drilling were higher than the maximum allowable limits of the logging equipment.

Geological Survey hydrologic studies on water wells generally less than 1,000 feet deep in the valley indicate average specific-yield values of about 10, 15, and 20 percent for the shallow deposits. (The specific yield of a rock or soil is the ratio of (1) the volume of water which, after being saturated, it will yield by gravity to (2) its own volume. The definition implies that gravity drainage is completed.) On the basis of geologic data, we assume these values can be extrapolated to a depth of 3,000 feet. Studies in other desert basins of California and Arizona indicate similar values. For basin depths more than 3,000 feet, specific-yield values are not readily determinable. However, based on evaluation of different types of geohydrologic data, the specific yield and the quantitiy of recoverable water from the deeper aquifers (see section "Thickness, Areal Extent and Specific Yield or Porosity of Vertical Zones 1–4") probably is about 5 percent for deposits greater than 8,000 feet deep, about 16 percent for deposits shallower than 8,000 feet but with water temperatures exceeding 100°C, and about 13 percent for deposits greater than 3,000 feet deep but with water temperatures less than 100°C.

METHODS OF COMPUTATION

The most reliable estimates of porosity were determined with a computer program utilizing data from a formation-density log and neutron-porosity log of well 92 (Bur. Reclamation well 127). The porosity was computed at 1-foot intervals and averaged about 25 percent for the logged interval of 204–1,400 feet below land surface (fig. 14). Unfortunately, the well is only 1,406 feet deep. However, only 5 miles northeast of this well, a sonic log was run in an oil test well (No. 82) to a depth of 7,988 feet below land surface. Porosity values from this sonic log were corrected for hole diameter and compaction of the formation with depth. The sonic porosity curve was then adjusted by shifting to provide a better correlation with the data from the shallow well. Computations of porosity from sonic logs are commonly too high in these types of sediments. Porosity values estimated by J. B. Combs (written commun., 1971) prior to this report by using data from a sonic log of well 82 are plotted for comparison (fig. 14).

Elsewhere in the valley, 6 miles southwest of Niland, the porosity computed from a gamma ray-neutron log of well 39 (IID 1) for the interval 64–1,700 feet below land surface was about 35 percent. Seven miles southeast of Brawley, the porosity from a compaction compensated sonic log of well 71 (Wilson 1) ranged from 18 to 28 percent below 4,000 feet. Both of the above values may be too large; the methods of computation are unreliable.

Utilizing the three logs from wells 82 and 92, a porosity-depth relation was determined (fig. 14). Using these values as a guideline, average porosity and specific yield were assigned for the rocks and deposits from the land surface to a depth of about 15,000 feet (figs. 9, 10, and 11).

USABLE AND RECOVERABLE WATER

CRITERIA FOR DEFINING TERMS

The water-quality criterion for usability of the water in storage is that the water shall

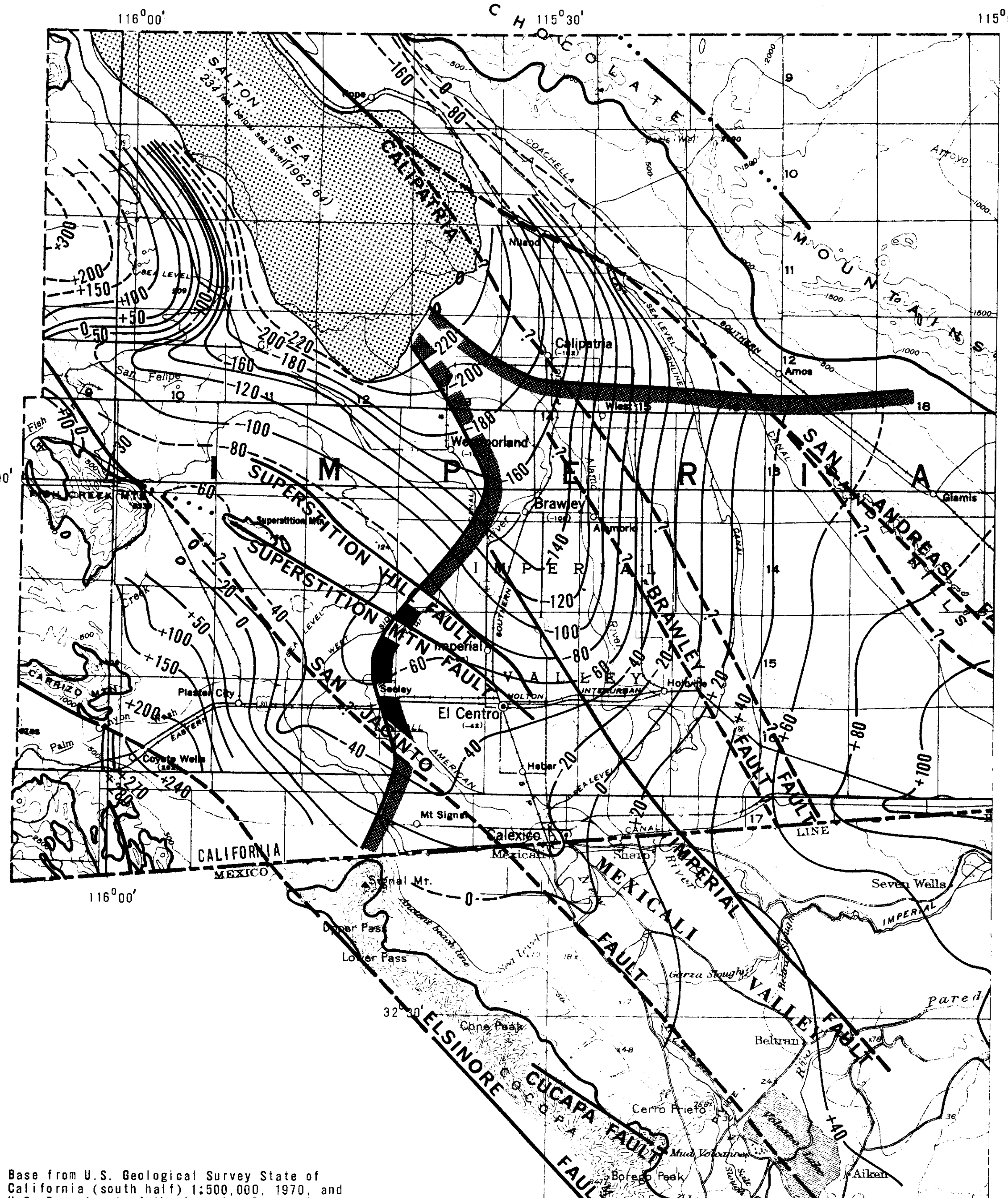


FIGURE 13.—Ground-water-level contours of shallow aquifer system, 1962 and 1964, in Imperial and Mexicali Valleys.

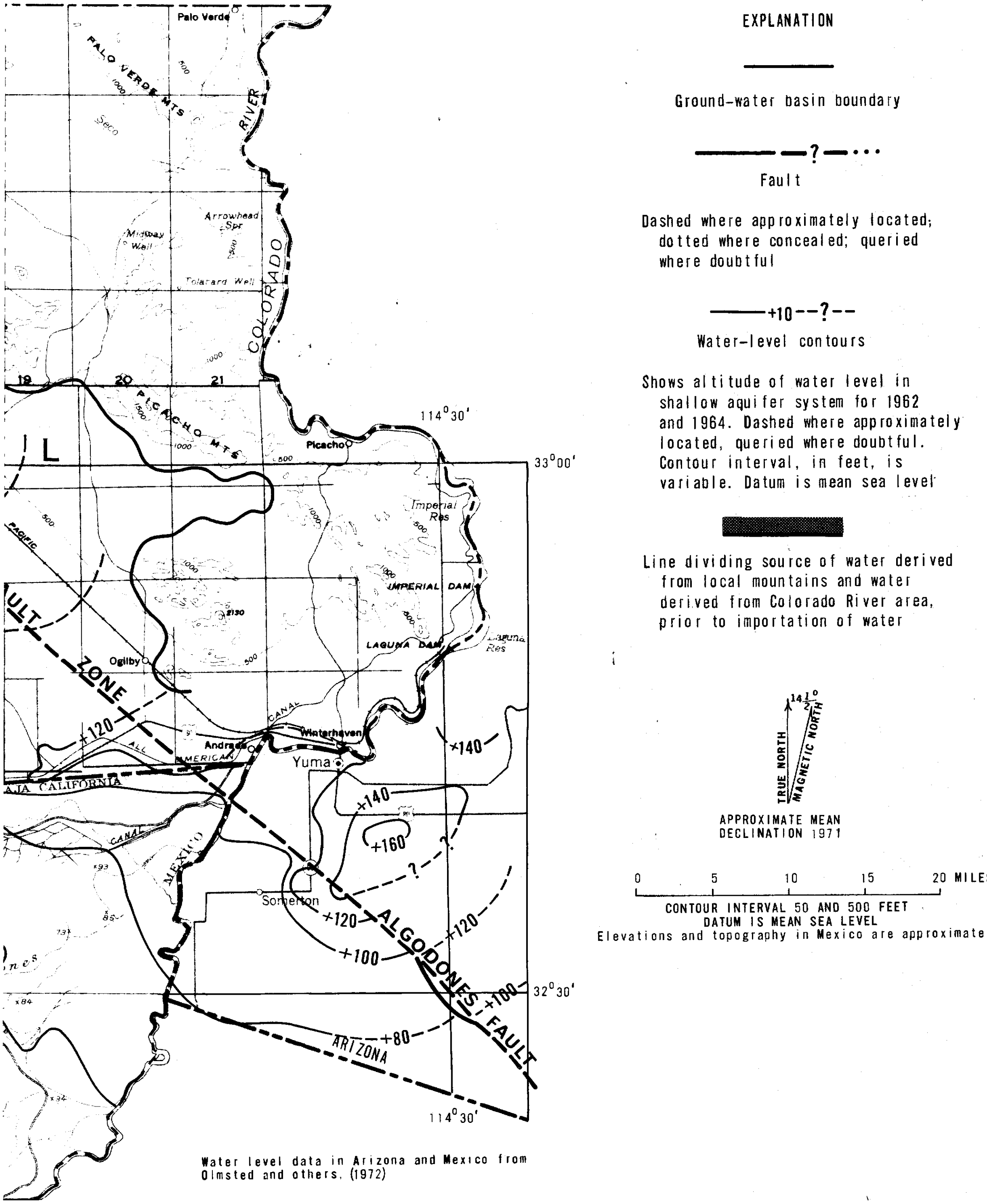


FIGURE 13.—Continued.

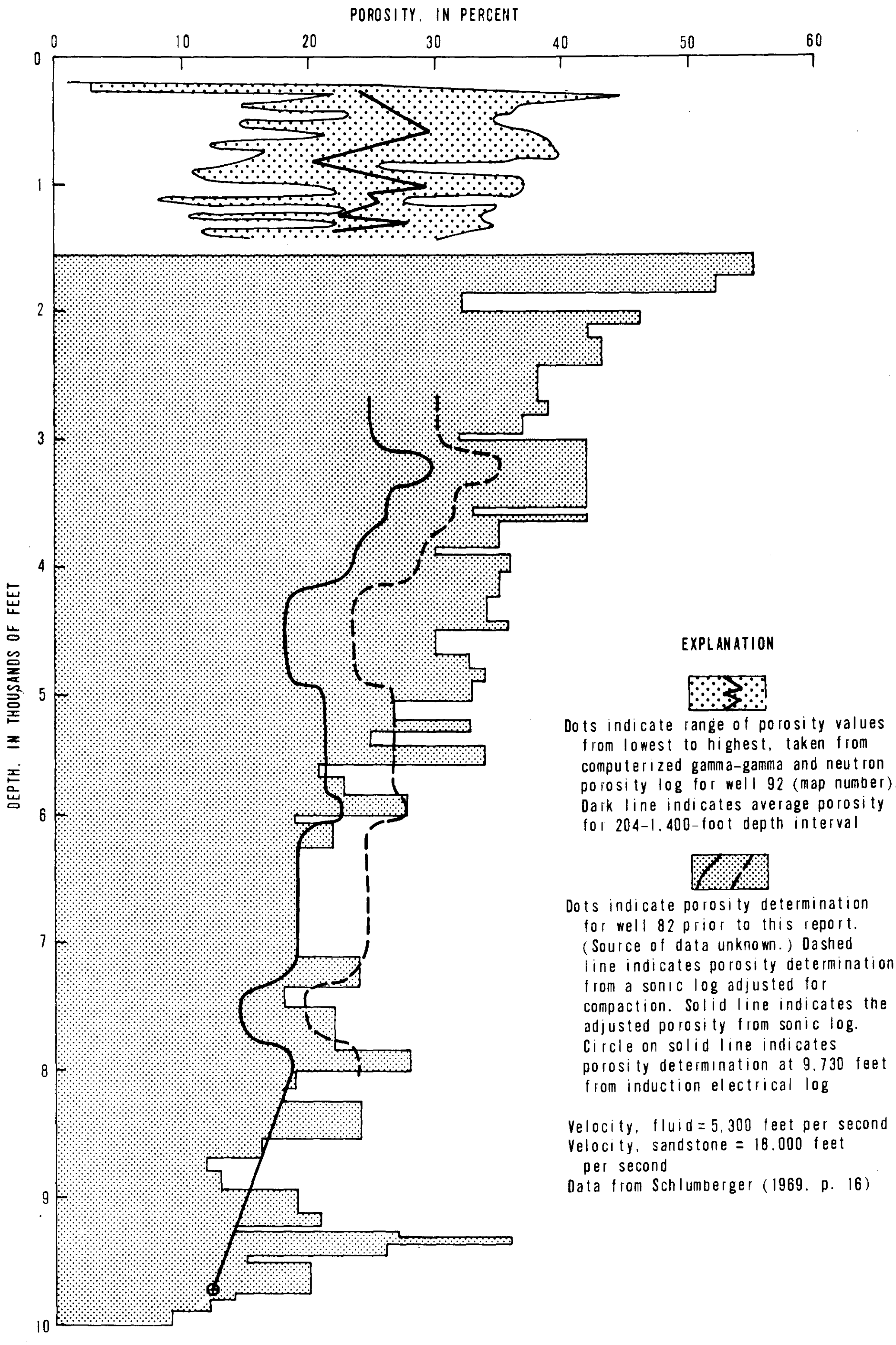


FIGURE 14.—Estimates of formation porosity from wells 82 and 92.

contain fewer than about 35,000 mg/l dissolved solids, regardless of the concentration of any specific ions. This decision by the Bureau of Reclamation was reportedly based on the following considerations:

1. It is unlikely that in Imperial Valley, wells can be drilled that will produce dry steam only, or even essentially only steam.
2. If wells produce both water and steam, the dissolved-solids content of the production water will sensitively control the economics of the operations. After separating the high-temperature steam, it would be possible to desalt a large percentage of the coproduced water, thus leaving as a hypersaline brine only a small percentage of the total, if the original water were of good quality. This brine could then be disposed of presumably either by reinjection into the aquifer system, by evaporation, or by some other means. To accomplish steam production and to provide water for desalting, it was decided that the water be classified as usable only if its initial dissolved-solids content is no greater than about 35,000 mg/l.
3. If wells produce only water at temperatures below the boiling point, intended for desalting (using supplemental energy), the same economic considerations outlined above apply to a large degree.
4. If wells produce water intended for blending directly with a source of desalted water, the lower the dissolved-solids content of the pumped water the greater the volume of the final blend; thus, an economic benefit results from starting with water containing fewer than 35,000 mg/l dissolved solids.

Determining whether or not water in storage is economically recoverable must ultimately be based on detailed knowledge of the aquifer system, the physical state of the fluid, and the type, kind, and location of wells, pumps, and production facilities designed for recovering the water. The operating procedures and practices also must be known in detail. Obviously such operating criteria cannot be developed for the Imperial Valley area at this stage of exploration and testing. Therefore, estimates of recoverable water, as the term is used in this report, are based on three assumptions:

1. Engineering plans can be made and sound operating procedures could be devised for withdrawing the water from wells over a very long period, if economical to do so. Limits would be imposed by economic considerations and the characteristics of the aquifers penetrated. Because economics are not considered, many usually limiting considerations, such as well spacings, pumping rates, and drawdowns, were ignored when classifying the water as being recoverable.
2. The physical characteristics of the aquifer system and the physical state of the fluid were the principal factors considered when deciding whether or not the water in storage is recoverable. Thus, the aquifer gross transmissivity and the permeability of the deposits, the porosity and lithology of the deposits, the thickness of the saturated deposits, and the temperature of the water were taken into account. In some parts of the basin-filling deposits the recoverable water was estimated to be virtually equal to the total porosity; in other parts, the recoverable water will be only as great as the estimated specific yield of the deposits. This distinction was made because we assumed that under some production procedures the water yielded will exceed the specific yield of the rocks where temperature is greater than 100°C.
3. The present pattern of water use in the central part of the valley and the irrigation practices there cause an aquifer boundary condition that would virtually preclude any dewatering of the shallow aquifers by pumping from wells. Annually more than a million acre-feet of water are applied to the land in excess of the consumptive use of crops to control soil salinity. Any reasonable attempt to mine water from the underlying shallow aquifers of very low transmissivity would meet with limited success because water available for diversion from the overlying network of shallow drains and

irrigation canals would ultimately prevent further drawdown. For this reason dewatering the upper water-bearing zone beneath the irrigated area seems infeasible. The recoverable water in that area, therefore, is considered nearly zero, and water storage in that area is not included in the estimates.

METHOD OF ESTIMATING USABLE AND RECOVERABLE WATER

To estimate usable and recoverable water in storage in the Imperial Valley area the following steps had to be completed:

1. Map the thickness of water-bearing deposits containing fewer than 35,000 mg/l dissolved solids.
2. Divide the water-bearing rocks and deposits into several convenient units or depth zones on the basis of approximately uniform permeability, porosity, specific yield, and temperature.
3. Determine the average porosity, permeability, and, in some cases, the specific yield of the water-bearing rocks and deposits of each unit or depth zone selected.
4. Map the thickness of water-bearing deposits in each selected unit or depth zone.
5. Measure the areal extent of the water-bearing deposits mapped in each selected unit or depth zone.
6. Compute the usable recoverable water in storage using the following equation:

$$S_{ur}=AmS_y \text{ or } S_{ur}=AmP_t,$$

in which S_{ur} is the approximate usable recoverable water in storage,
A is the area of the storage unit,
m is the thickness of saturated deposits,
and S_y, and P_t are the specific yield or approximate total porosity of the water-bearing deposits, whichever is applicable.

THICKNESS OF WATER-BEARING ROCKS AND DEPOSITS

To estimate usable and recoverable water in storage in the Imperial Valley area, the first step necessary was to estimate the maximum thickness of water-filled rocks and deposits. Fortunately, the maximum thickness of water-bearing rocks was previously estimated by Rex (1970). His map was based mainly on gravity studies by Biehler (1964), supplemented by some seismic data. During this study, available logs of wells drilled near the basin margins were examined. In general, these data confirm the interpretations of the bedrock structure shown by Rex, and his map is reproduced in essentially unmodified form in figure 4. That map was also used in preparing the hydrologic sections (figs. 9, 10, and 11). Our criterion for usability (35,000 mg/l) and our conceptual model of the system exclude the deeper parts of the basin, however.

All available water-quality data, including both chemical analyses of water and electrical logs of test wells, were examined. These data were considered in terms of the elements and mechanisms proposed for the conceptual model of the system and were then interpolated throughout the basin between points of control to estimate the total thickness of water-bearing rocks and deposits containing fewer than about 35,000 mg/l dissolved solids in the contained water. Our concept of the thickness of the rocks and deposits containing usable water, therefore, is shown in the sections (figs. 9, 10, and 11) and in figure 15.

On the basis of this interpretation of available data, the deposits of interest are a maximum of about 15,000 feet thick a few miles south of Holtville and about 13,000 feet thick north of Brawley. They thin to zero locally along the basin margins on the east and west, but elsewhere, particularly along the north margin of Imperial Valley and along the international border, they extend beyond the area where usable and recoverable water in storage was estimated.

AREAL AND VERTICAL EXTENT OF STORAGE UNITS

For purposes of estimating usable and recoverable water in storage, four areal units (fig. 16) and four vertical water-bearing zones were established (fig. 9). The average porosity or specific yield of the deposits, whichever is applicable, was estimated for each vertical zone. The four areal storage units are called Sand Hills, East Mesa, main valley, and West Mesa (fig. 16). The four vertical zones are numbered 1–4 (fig. 9).

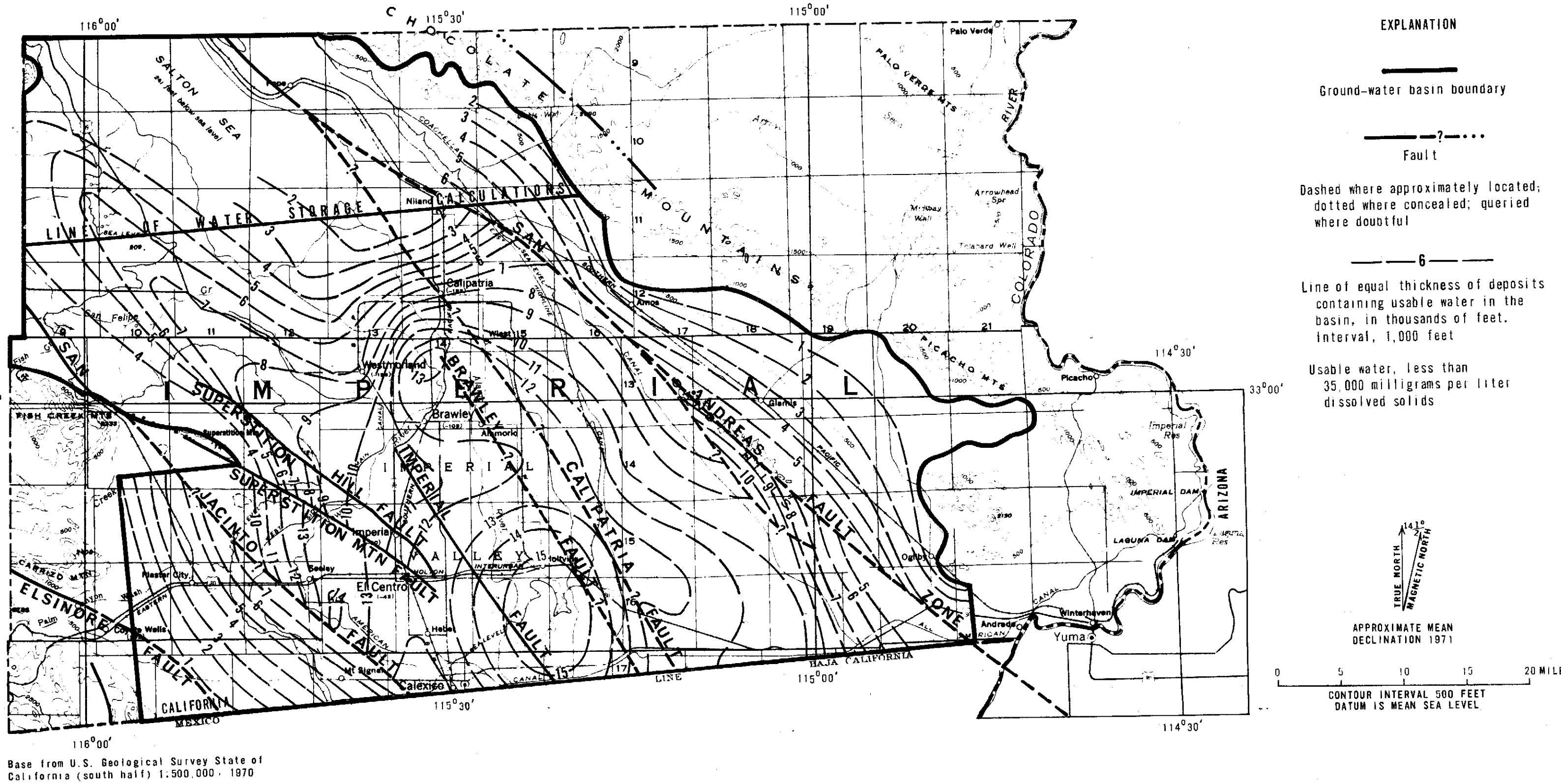


FIGURE 15.—Thickness of deposits with total usable water.

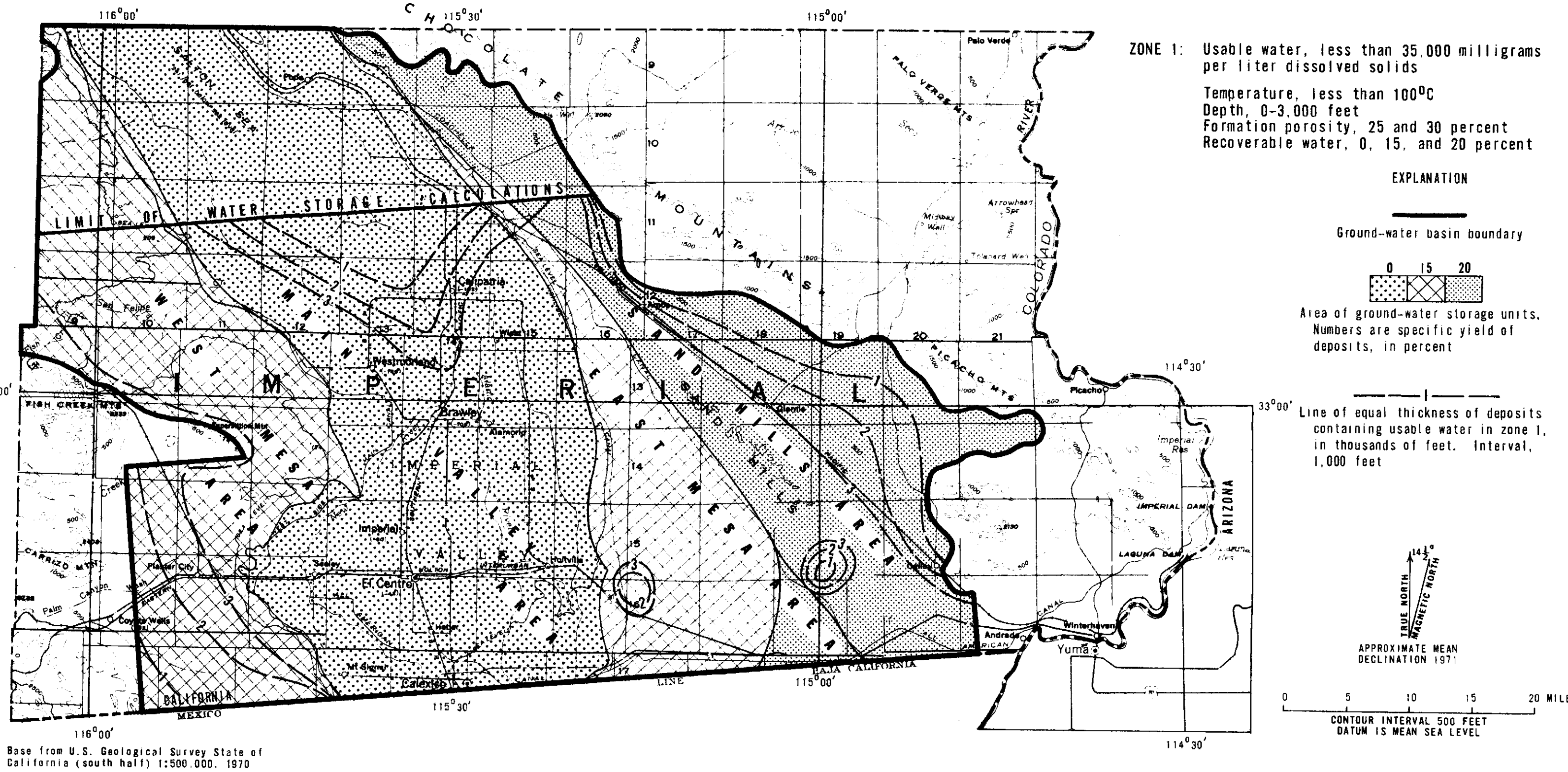


Figure 16.—Thickness of deposits with usable water in zone 1.

As a second objective, usable and recoverable water probably having a temperature greater than about 150°C was also estimated. This estimate was made because a temperature of at least 150°C is considered marginal to produce commercial steam for power generation; under present technology a temperature of 180°C may be required. Finally, the quantity of water in storage that was probably derived from local sources and from the Colorado River was estimated. This was accomplished in zone 1 by using the ground-water flow lines shown in figure 13 to subdivide the storage units into areas where water is derived from local sources and the Colorado River. The estimates were accomplished for zones 2, 3, and 4 by using the ground-water divide shown in figure 7 to subdivide the storage units into areas where water is derived from the Colorado River and local sources.

Ground-water flow in the aquifers deeper than about 3,000 feet is probably downward from the shallower aquifers and radially toward each area of anomalously high heat flow where water-convection cells exist (Salton Sea and Cerro Prieto geothermal fields) or are postulated at great depths. Inferred ground-water flow lines are represented by arrows in figure 7. The position of the ground-water divide, as shown in figure 7, is inferred on the basis of the assumed flow lines.

The separation of water in zone 1 derived from local sources and the Colorado River was made on the basis of our concept of the flow system under natural conditions before a large part of the area, called the main valley area herein, was placed under irrigation. Therefore, some water derived from the Colorado River and used for irrigation may now be in storage in the area shown as containing locally derived water in figure 13. This storage, however, is probably minor in amount and is probably restricted to the upper part of the deposits in zone 1.

THICKNESS, AREAL EXTENT, AND SPECIFIC YIELD OR POROSITY OF VERTICAL ZONES 1–4

Four vertical zones were established on the basis of having approximately similar rock properties. The generally similar conditions and rocks made it possible to assume and then compute an average porosity or specific yield for the entire volume of rock within the depth intervals considered. Because the thickness of each depth zone varies areally, maps of each zone were prepared showing lines of equal thickness (figs. 16, 17, 18, and 19). The thickness of each zone is also shown in the three hydrologic sections (figs. 9, 10, and 11).

Zone 4 (fig. 17) is the deepest of the four vertical subdivisions of the water-bearing rocks and deposits. As established for purposes of this report, it contains all the reservoir rocks that contain usable and recoverable water in storage at a depth greater than 8,000 feet. Thus, vertical depth-zones 3 and 4 are separated by a somewhat aribitrary line about 8,000 feet below the surface. The basis for this separation was the estimated downward decrease in porosity, the lithologic changes caused by increased metamorphism with increasing temperature at depth, and the indicated very low permeability of the rocks penetrated by wells below a depth of about 8,000 feet, as determined by interpretation of electric logs. Conditions of temperature and pressure in the deep wells make interpretations based on existing electric logs uncertain. Convection, or caking of drilling mud, or unexplained phenomena, make it impossible to interpret the formation-water quality for many wells or even to detect the presence of relatively permeable or impermeable beds. Nevertheless, on the basis of available data, in general the rocks below 8,000 feet probably have very low permeability, are fractured, and have an average porosity of about 5 percent.

Because most of the contained water is at a high temperature, above 150°C, most of the water could probably be recovered from wells. The entire volume of water, estimated at 5 percent of the total volume of the rock, could be recovered, however, only if pressures are eventually reduced sufficiently to allow flow in the vapor phase.

The maximum thickness of zone 4 is about 7,000 feet in an area south of Holtville (fig. 17). The line of zero thickness encloses an area of about 1,000 sq mi in the southcentral part of the storage units beneath the valley floor. The estimated total volume of the rocks is

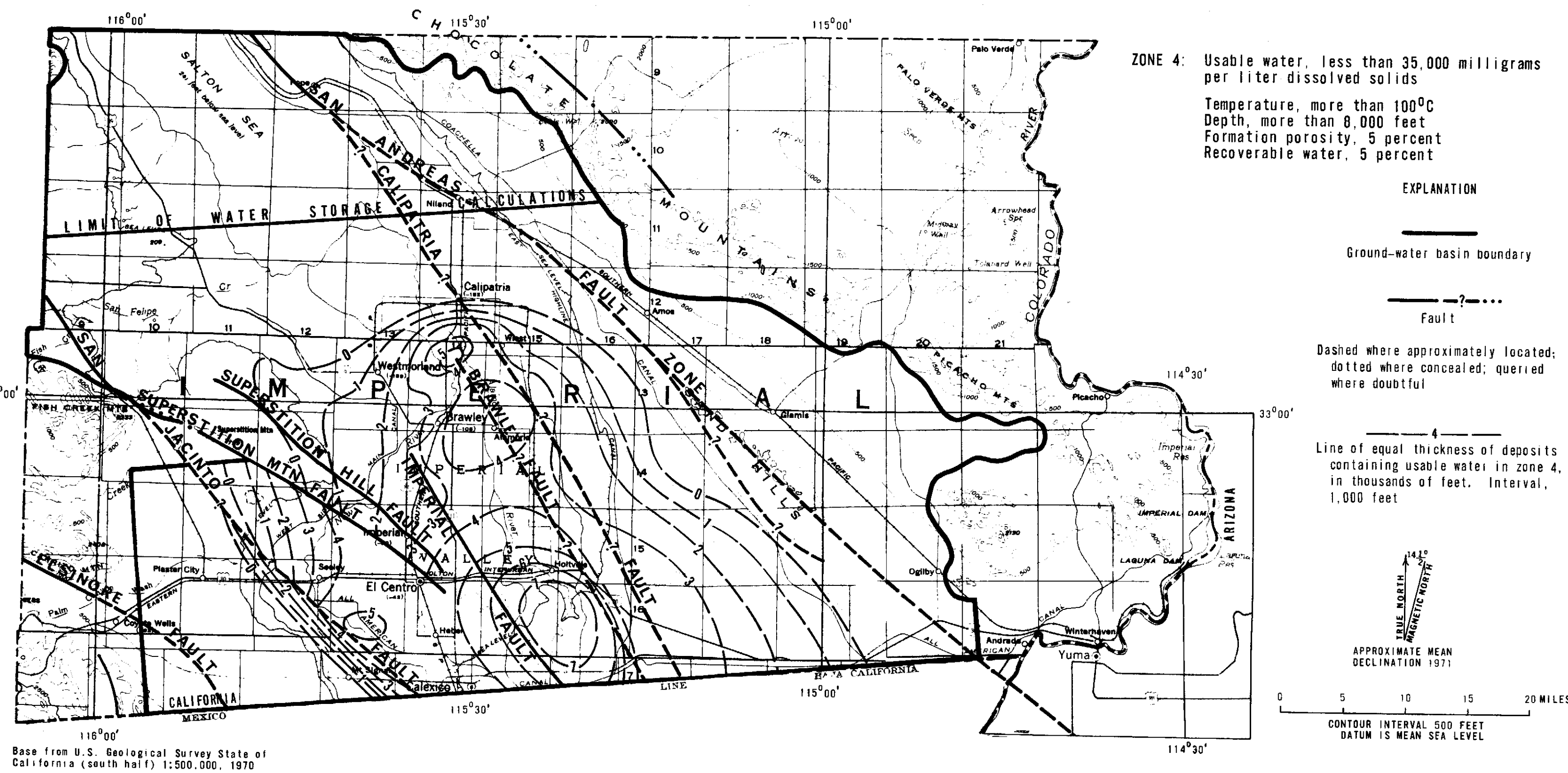


FIGURE 17.—Thickness of deposits with usable water in zone 4.

about 1.9 billion acre-feet; about 100 million acre-feet of recoverable water is in storage in zone 4 (see table 3).

Zone 3 (fig. 18) overlies zone 4; it is much larger in areal extent than zone 4, not as thick, on the average, but contains much more water in storage. The porosity is estimated to average 20 percent, and the temperature of all the contained water is 100°C or greater (figs. 9, 10, and 11). The low permeability of some of the rocks, the small thickness in some localities, and the lack of very high water temperatures in most of the depth zone, however, probably will make it impossible to rocover water from some of the rock pores. We believe that the low permeability will necessitate using closely spaced wells. It will probably not be economically feasible to drill wells at such close spacing as would be required to recover all the water; therefore, we believe that a significant percentage of the water will probably be retained in pores of the rocks, regardless of production methods used. The recoverable water will probably average more than the specific yield but less than the total porosity; the recoverable water may average about 16 percent of the total volume of saturated reservior rock.

The maximum thickness of zone 3 is about 7,000 feet in a small area about 20 miles east of Holtville (fig. 18). The line of zero thickness encloses an area of about 1,700 sq mi. The estimated total volume of the rocks is also about 1.9 billion acre-feet; and about 300 million acre-feet of recoverable water is in storage in zone 3 (see table 3).

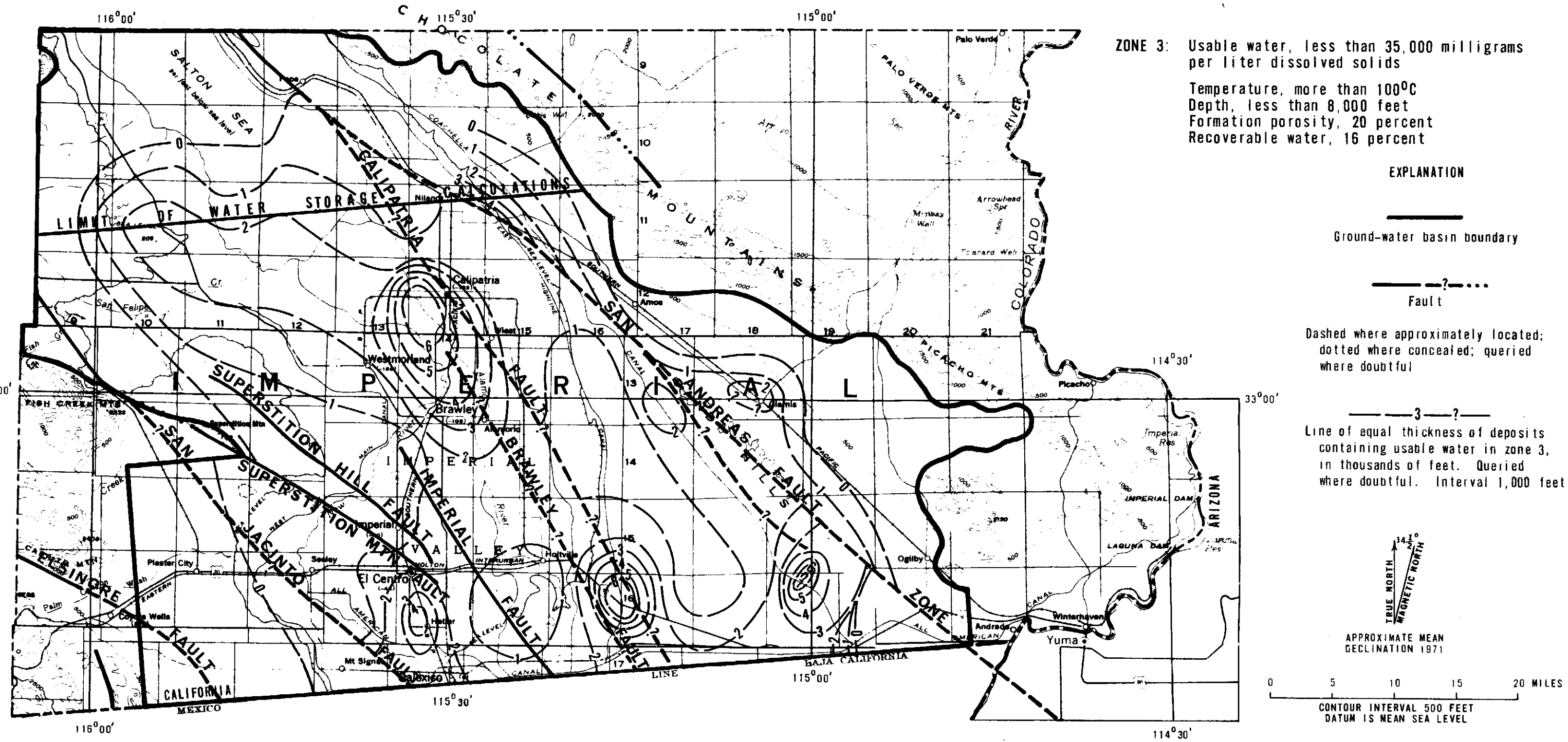
As defined earlier, zone 2 extends from about 3,000 feet downward to the top of zone 3 at the 100°C isothermal surface; thus, zone 2 contains water at a temperature less than 100°C (figs. 9, 10, and 11).

The average porosity of the materials of zone 2 (fig. 19) probably is about 20 percent. However, because of the low temperature of the water, the total porosity is not a good index of the recoverable water in storage. Rather, the specific yield of the rocks and deposits must be used, assuming full drainage by gravity, to estimate the amount of recoverable water. An acceptable estimate of specific yield can be derived by multiplying estimated porosity by two-thirds, if sufficient data from well logs are unavailable on which to base direct estimates of specific yield. Thus, the specific yield of the deposits in zone 2 is estimated to average 13 percent.

The maximum thickness of zone 2 is about 4,000 feet in three areas of anomalously high temperature (fig. 19). In two areas of anomalously high heat flow in the southeast part of Imperial Valley, zone 2 is presumably absent because of the high water temperatures at shallow depth (figs. 11, 19). The lines of zero thickness enclose an area of about 1,650 sq mi. The total estimated volume of the reservoir of zone 2 is about 2.8 billion acre-feet; about 360 million acre-feet of recoverable water is in storage in zone 2 (see table 3).

Zone 1 (fig. 16) extends downward from the water table near the surface to a maximum depth of 3,000 feet, or to the bedrock surface or the 100°C surface, whichever was less. Only in this zone was it possible on the basis of available data to portray the areal as well as the vertical variation in specific yields of the deposits. The Bureau of Reclamation requested that water in storage beneath each of the subunits be estimated separately because much of the land is Federally owned and has been withdrawn from the public domain for reclamation purposes. Thus, zone 1 was subdivided into four storage subunits (fig. 16). From east to west these are called the Sand Hills, East Mesa, main valley, and West Mesa storage units.

The average specific yield of the deposits of zone 1 beneath the Sand Hills subunit is estimated to be 20 percent. Beneath the East and West Mesa subunits, the specific yield of the deposits of zone 1 is estimated to be 15 percent, except in a small part of the southeast corner of East Mesa where it is estimated to be 20 percent. Beneath the main valley area, however, the irrigated area constitutes a recharge-boundary condition for the aquifers underlying the irrigated land, and dewatering the deposits is probably not feasible. Therefore, draining water from zone 1, main valley subunit, is probably not feasible, and the specific yield is considered to be virtually zero (see table 2). If water is pumped from this main valley area, it will almost certainly be derived



Base from U.S. Geological Survey State of California (south half) 1:500,000, 1970

FIGURE 18.—Thickness of deposits with usable water in zone 3.

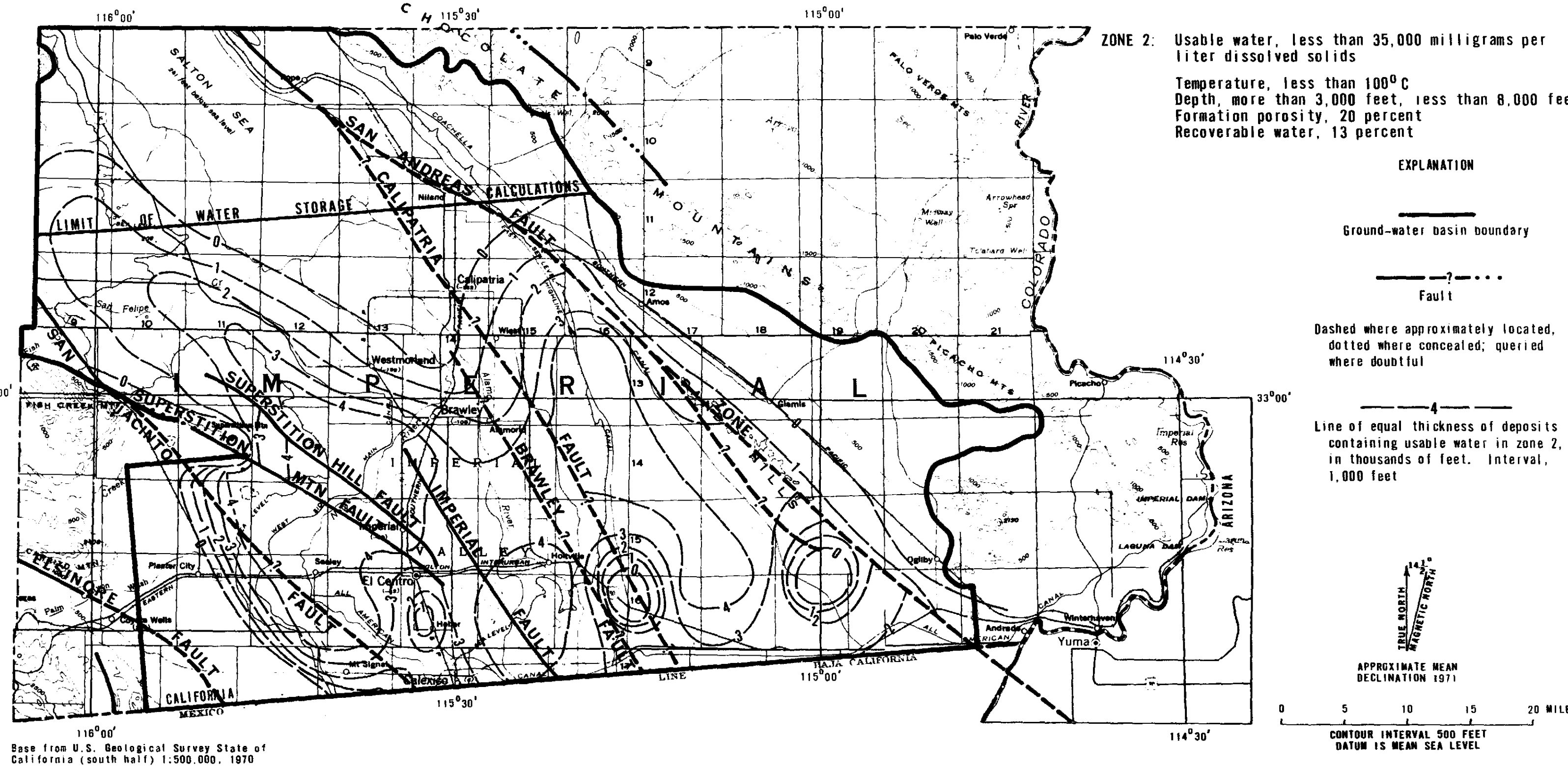


FIGURE 19.—Thickness of deposits with usable water in zone 2.

TABLE 2.—*Usable and recoverable water at temperature of 150°C or more*

[Estimates in millions of acre-feet]

Source	Storage in areal subunits				Rounded total	Percentage of total
	Sand Hills	East Mesa	Main valley	West Mesa		
Colorado River	10	48	69	0	127	64
Local	.91	2.9	60	5.6	70	36
Rounded total	11	51	129	5.6	197	—

directly from the canals that drain the irrigated land.

The area of the Sand Hills subunit is about 450 sq mi, that of the East Mesa subunit about 350 sq mi, and that of the West Mesa subunit about 465 sq mi. About 350 million acre-feet of usable and recoverable water is contained in zone 1 (see table 3).

WATER AT TEMPERATURES MORE THAN 150°C

The areal extent of usable water at a temperature more than about 150°C is shown in figure 20. Such water is widespread; we believe it underlies almost all of the Imperial Valley area and is absent only along the marginal parts of the valley beneath strips of land a few to 10 or more miles wide. The thickness of rocks containing usable water at 150°C or more ranges from 0 to more than 8,000 feet. The estimated average porosity of the reservoir rock is about 10 percent.

Figure 20 shows the thickness of four known areas with deposits containing usable hot water at more than 150°C. Southeast of Holtville the deposits are more than 8,000 feet thick, near Heber about 5,000 feet thick, and near both Ogilby and Westmoreland about 6,000 feet thick. In much of the area, however, the thickness of deposits with usable water at a temperature of 150°C or greater is only 1,000–2,000 feet.

The total estimated usable water in storage having a temperature of 150°C or more (table 2) is rounded to about 200 million acre-feet.

On the basis of the data available regarding the probable source of the water, about 64 percent or about 127 million acre-feet is derived from the Colorado River, and 36 percent or about 70 million acre-feet is from local sources.

SUMMARY OF USABLE AND RECOVERABLE WATER

Preliminary estimates of total usable and recoverable water in storage are summarized in table 3. Total usable and recoverable water in storage is estimated to be 1.1 billion acre-feet. This compares to a quantity in storage of 1.6–4.8 billion acre-feet previously estimated by Rex (1970, p. 14). Of that amount, about 190 million acre-feet is contained in the four vertical depth zones beneath the Sand Hills storage unit (fig. 16), about 280 million acre-feet underlies the East Mesa area, about 430 million acre-feet is beneath the main valley irrigated area, and about 215 million acre-feet is beneath the West Mesa area.

TABLE 3.—*Summary of usable and recoverable water in the Imperial Valley area, California, containing less than 35,000 mg/l dissolved solids*

[Estimates in millions of acre-feet]

Vertical depth zone	Storage in areal subunits				Total	Percentage in each depth zone
	Sand Hills	East Mesa	Main valley	West Mesa		
1	126	103	0	120	349	31
2	28	89	181	63	360	32
3	38	67	170	29	304	28
4	.1	19	77	2.4	99	9
Rounded total	190	280	430	215	1,100	—
Percentage in each areal subunit	17	25	39	19	100	

TABLE 4.—*Summary of usable and recoverable water in storage derived from the Colorado River and local sources*

[Estimates in millions of acre-feet]

Vertical depth zone	Storage in areal subunits				Total	Percentage in each depth zone
	Sand Hills	East Mesa	Main valley	West Mesa		
Zone 1:						31
Local	16	6	0	119	141	
Colorado River	110	97	0	.9	208	
Zone 2:						32
Local	2.6	4.7	75	63	145	
Colorado River	25	84	106	0	215	
Zone 3:						28
Local	5.3	4.8	68	29	107	
Colorado River	32	63	102	0	197	
Zone 4:						9
Local	0	0	24	2.4	26	
Colorado River	.1	19	53	0	72	
Totals:	191	279	428	214	1,112	—
Local	24	16	167	213	420	38
Colorado River	167	263	261	.9	692	62
Percentage of total:						
Local	13	6	39	100	38	
Colorado River	87	94	61	0	62	

The vertical distribution (fig. 9) of the usable and recoverable water in storage is about as follows: vertical depth-zone 1 (from the water table to a depth of 3,000 ft in most of the area), about 350 million acre-feet; depth-zone 2 (from 3,000 ft to a water-temperature depth of 100°C in most of the area), about 360 million acre-feet; depth-zone 3 (from a water-temperature depth of 100°C to a depth of 8,000 ft in most of the area), about 300 million acre-feet; and depth-zone 4 (at a depth greater than 8,000 ft), about 100 million acre-feet.

Preliminary estimates of total usable and recoverable water in storage derived from local sources and the Colorado River are summarized in table 4. Of the approximate total 1.1 billion acre-feet in storage, about 420 million acre-feet or about 38 percent was probably derived from local sources and about 690 million acre-feet or about 62 percent was probably derived from the Colorado River.

RELIABILITY OF THE ESTIMATES

The probable percentage error for the estimates compiled in this report cannot be determined. Data are not available on which such error estimates could be based. In fact, if it had been required at this stage that such estimates be based on standard methods of computation, using only data that would ordinarily be termed of minimum acceptable accuracy, in the amount ordinarily acceptable, and having the usually required pattern of distribution throughout the system, it would have been impossible to compile the estimates.

The logic on which the great extrapolations could be based had to be developed by formulating a conceptual model of the sedimentary basin, considering the elements and mechanisms of the hydrothermal system. Both models had to take into consideration all available data and information available at the present time (June 1971). Therefore, the accuracy of the estimates of usable and recoverable water in storage in the system is directly related to how adequately the conceptual model of the system represents the prototype. How nearly the conceptual model agrees with the prototype cannot be determined until considerable additional data are collected and much further research is completed. Until additional data are generated and much new research is done, the estimates must be considered usable engineering approximations; all planning, including development of the resources, research, and future data-collection programs, should be based on that understanding.

SIGNIFICANCE OF PRODUCTION METHODS

Although the estimates of recoverable water (tables 2, 3, and 4) in the Imperial Valley area were based on an assumption that all water in

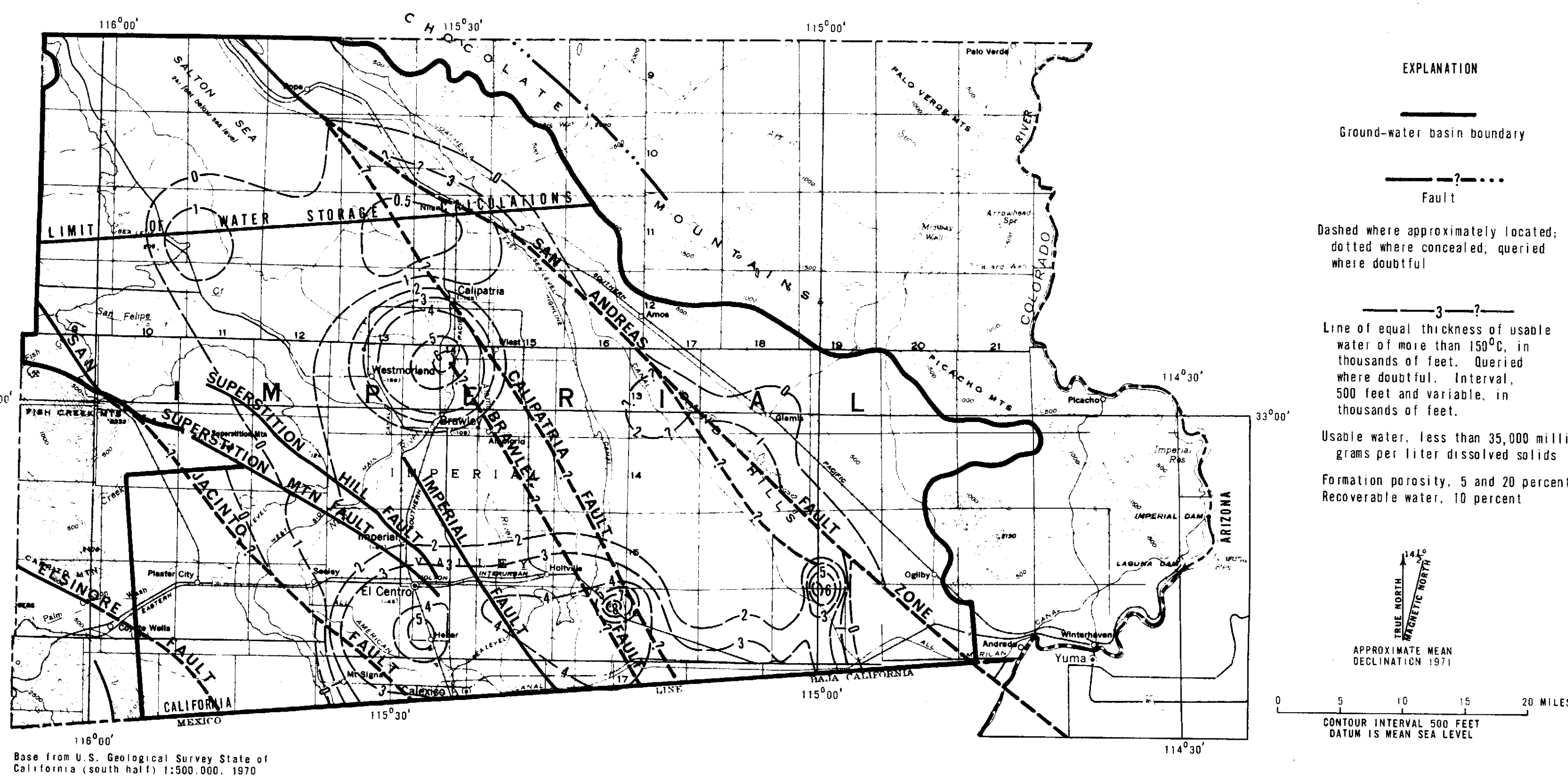


FIGURE 20.—Thickness of deposits with usable water of more than 150°C.

storage would be recoverable through wells by some means, production of much of the water may not be economically feasible. For example, average yields of wells penetrating depth-zone 1 beneath the East and West Mesa areas where water temperatures are less than 100°C may be a few hundred gallons per minute with large drawdowns (many tens of feet). The problem of small yields may also occur where wells penetrate depth-zone 2.

Large-scale subsidence of the land surface following production might require reinjection of water from the ocean or other sources to maintain reservoir pressures, adding further to the costs. Only further drilling, testing, and experiments can provide a basis for determining whether or not the water can be recovered economically.

Furthermore, the problem of preventing large-scale subsidence will probably be compounded by a need to recharge the deep aquifers by using injection wells. On the basis of available geologic data and estimates of aquifer transmissivity and rock permeability, it is very unlikely that the deep parts of the system can be recharged by spreading water in surface basins. The vertical permeability is probably much too low in most of the basins. Recharging the deep aquifers using injection wells will greatly increase costs over those experienced in other areas where recharge can be accomplished through use of water-spreading basins on the surface.

In addition to the economic and environmental problems, there are many legal factors to be considered that might influence utilization of the resource. The significant legal factors are summarized in a report by the California Geothermal Resources Board (1971).

The cost of pumping water from wells increases with lift. The electric power, in kilowatthours (kwhr), required to lift 1 acre-foot of water 1 foot can be calculated from the formula:

$$\text{kwhr/acre-ft/ft} = \frac{\text{gallons in 1 acre-ft} \times \text{weight of 1 gallon of water}}{\text{foot-pounds per minute for 1 kilowatthour}} \times \frac{100}{\text{pumping plant efficiency, in percent}}$$

$$= \frac{325{,}850 \times 8.336}{44{,}254 \times 60} \times \frac{100}{\text{pumping plant efficiency, in percent}}$$

$$= 1.02 \times \frac{100}{\text{pumping plant efficiency, in percent}}$$

Conversion factors:

1 acre-ft = 325,850 gallons (gal)

1 gal water = 8.336 pounds (lbs)

1 kilowatt (kw) = 44,254 foot-pounds per minute (ft-lbs/min)

1 kilowatthour (kwhr) = 44,254 × 60

Estimating prospective pumping-plant efficiency for future wells is not presently possible. Pumping costs, however, would be very high if a large percentage of the total estimated usable and recoverable water in storage in the basin were pumped from wells. An example of such costs, using a pumping-plant efficiency of 50 percent, probably a very optimistic estimate if pumps are set at great depth, is included below to illustrate the economics of dewatering deep aquifiers.

The power requirements to pump 1 acre-foot at a rate of 1 cfs (cubic foot per second) at a 5,000-foot head for the wire-to-water efficiency of 50 percent, using electrical energy cost of $0.01 per kilowatthour, would be about as follows:

$$\text{kwhr/acre-ft/ft} = 1.02 \times 100/50 = 2.04$$

$$\text{Cost/acre-ft} = 2.04 \times 5{,}000 \times \$0.01 = \text{about } \$100.00$$

Cost of wells and pumps should also be considered. Mean costs of deep 8- to 12- inch wells in sandstone can be crudely estimated using an empirical formula derived by the Illinois State Water Survey (written commun., 1968):

$$\text{Well cost} = 0.029d^{1.87}$$

where d is depth of well, in feet. Thus, a 3,000-foot well would cost about $90,000. Wells 8,000 feet deep might cost more than $210,000 each.

If as much as 1,000 feet of pumping lift could be economically justified, about 100 million acre-feet of water, all in depth-zone 1 beneath the Sand Hills and East and West Mesa areas, might be economically recoverable. Of course, at high temperatures (> 150°C) wells do produce steam and water without being pumped, if the initial hydrostatic head is removed by gas lifting or other means. Production of all such water and steam, however, presumably will be from zones greater than 1,000 feet beneath the surface. If deep wells produce both water and steam without being pumped, additional water would be recoverable if high well costs, repressurization costs, and air and water pollution prevention measures do not prevent such production.

In summary, economic studies are needed to determine the feasibility of recovering the 1.1 billion acre-feet of water estimated in this report as being recoverable. Such studies may indicate that recoverable water is only about 100 million acre-feet at a temperature less than 100°C, less than 100 million acre-feet at higher temperature, and less than 200 million acre-feet from all sources.

POSSIBLE CHANGES IN THE FLOW REGIME

Another objective of this report was to describe briefly and in general terms the possible changes in the water inflow-outflow relations that might result from large-scale extraction of the recoverable water in storage. Depending on where wells are located, their yields, drawdowns, and duration of pumping, several changes in the flow regime could be induced as follows:

1. Ground-water flow might change in quantity or be induced to reverse direction across the international boundary.
2. More water might be induced to percolate from the large irrigation canals to the underlying ground-water body.
3. Ground water derived from local sources might be induced to flow into or toward producing wells in areas formerly containing only water derived from the Colorado River.
4. Ground water derived from the Colorado River might be induced to flow into or toward producing wells in areas formerly containing only water derived from local sources.
5. Ground water, which under natural or present-day conditions flows upward to enter the drainage systems on the surface, might be diverted to enter pumping wells.
6. Water that now presumably flows downward to recharge deep water-convection systems might be diverted by production wells and thus cause changes in the deep inflow-outflow systems.
7. Changes in chemical quality of water might occur as a result of disturbing water-quality interfaces by pumping.
8. Ground water might be diverted downward from the land surface, rivers, or drainage channels in the irrigated area, and thus be diverted from the Salton Sea.

Other and unforeseen changes in the ground water inflow-outflow relations might also occur. The point is that any large-scale water production will induce changes in the system and these are now impossible to predict quantitatively. A very large additional quantity of special data would be required before it would be possible to make a quantitative prediction of the nature and magnitude of the changes that would result if specified production stresses are imposed on the system.

POSSIBLE ENVIRONMENTAL HAZARDS

We have not attempted to foresee or analyze the consequences of all possible practices that might result in environmental hazards. The most serious problems may result from land subsidence, induced seismic activity, and air, water, and noise pollution. These are briefly discussed in the following sections of the report.

LAND SUBSIDENCE

One of the potential hazards of ground-water extraction in Imperial Valley, either for geothermal power or for water supply, is the threat of land subsidence. Whenever fluids are mined from a ground-water reservoir—that is, withdrawals exceed the recharge rate and reservoir pressures continue to decline—land subsidence may occur. Throughout much of the developed area of Imperial Valley, subsidence would cause costly damages; in outlying undeveloped areas, subsidence might be tolerated. In either setting, the likelihood of subsidence resulting from the extraction of reservoir fluids must be fully considered, and the hydrogeologic parameters affecting the magnitude, extent, and rate of subsidence should be understood.

Subsidence results from the compaction of compressible beds of the aquifer system as effective stresses are increased by fluid-pressure reduction (Lofgren, 1968). The magnitude of the subsidence is dependent on the effective stress increase caused by the pressure drop, the compressibility of the deposits, the thickness of the compressible beds, the time the increased stress has been applied, and also on the past stress history—whether the increased stress is being applied for the first time or has been attained or exceeded previously. Although a small part of the subsidence may be elastic in nature and tend to rebound when the stress is removed, most of the change is nonelastic and nonrecoverable.

Water-level fluctuations in a ground-water reservoir cause effective stresses in the following two ways (Lofgren, 1968, p. B225):

1. A rise of the water table increases the buoyant support of the sand grains in the zone of the change, and a decline decreases the buoyant support; these changes in gravitational stress are transmitted downward to all underlying deposits.
2. A change in position of the water table or in the fluid pressure in a confined system, or both, may induce vertical hydraulic gradients across confining or semiconfining beds and thereby produce seepage stresses. These stresses are algebraically additive to the gravitational stress that is transmitted downward to all underlying deposits.

Land subsidence caused by the exploitation of oil and gas resources and by intensive pumping of ground water is relatively common throughout the world (Poland and Davis, 1969). As in oil-field or artesian ground-water production, a direct relation exists between subsidence and fluid-pressure decline in a geothermal field. Subsidence can be minimized or prevented by maintaining fluid pressures by either natural or artificial recharge. Also, the lateral extent of subsidence effects is sometimes defined by faults that are barriers to fluid flow. Recently, subsidence has been related to the extraction of geothermal waters in Wairakei, New Zealand (Hatton, 1970; Hunt, 1970) and Cerro Prieto, Mexico (Eduardo Paredes, oral commun., 1971). Although the geologic setting at these locations varies considerably, the basic cause of the subsidence is the same—the reduction of fluid pressure causing a marked increase in effective stress.

At Wairakei (Hatton, 1970) the area affected by subsidence exceeds 25 square miles, and the maximum subsidence rate is about 1.3 feet per year. Total subsidence exceeds 10 feet and, of particular significance, the area of maximum subsidence occurs outside the production field. At Cerro Prieto subsidence has been measured 7 miles outside the well field even though extensive production has not begun (Eduardo Paredes, oral commun., 1971). Corresponding effects could occur in Imperial Valley, unless provisions are made to maintain reservoir pressures.

Most of the parameters for predicting subsidence in Imperial Valley—such as anticipated pressure declines, thickness and compressibilities of the water-bearing deposits, and lateral extent of fault blocks—are not well known. Both fluid pressures and surface bench marks should be carefully monitored to measure the effects of production. Because Imperial Valley is tectonically active and may be subsiding naturally, provision should be made in the monitoring program to differentiate tectonic subsidence and also surficial compaction of shallow deposits from subsidence caused by geothermal development.

One of the considered proposals of the Imperial Valley development, and the principal reason for this ground-water storage appraisal, is the extensive production of ground water. Water-bearing deposits extend from near land surface down to practicable pumping depths and have a large storage capacity. Can this shallow reservoir be exploited without causing subsidence?

Experience in many areas of intensive pumping, particularly in the San Joaquin (Lofgren and Klausing, 1969; Poland and Davis, 1969) and Santa Clara (Poland, 1969) Valleys of California, indicates that ground water cannot be mined from these unconsolidated or semiconsolidated deposits without causing land subsidence. Particularly in the confined aquifer systems a direct relation exists between pumpage and land subsidence. Water pumped from a confined reservoir not recharged at the same rate by natural or artificial recharge is mined from the formation and causes subsidence.

In areas studied, the ratio of subsidence to head decline varies considerably, depending on the parameters discussed above. In general, 1 foot of surficial subsidence occurs for each 10–50 feet of long-term artesian-head decline. In several interior areas of heavily pumped basins, the volume of water pumped about equals the volume of subsidence it produces. This suggests that little or no recharge is getting to these parts of the reservoir.

As in other heavily pumped basins of the arid West, extractions in Imperial Valley that cause water levels to decline to new low levels each year will cause continuing subsidence. In parts of the valley long-term subsidence might be of little consequence; in other areas damages would probably be prohibitive.

SEISMIC ACTIVITY

Much scientific literature has accumulated in recent years on problems related to the disposal of liquid wastes underground. Piper (1969) has reviewed the overall subject, and his report included an extensive list of references on the subject. In regard to the hazard of induced seismic activity by either fluid withdrawal or injection, however, experience is much more limited. That fluid pressure and temperature changes caused by water removal or injection in systems such as the Salton Trough hydrothermal system can cause earthquakes or seismic activity has not been proved. However, earthquakes have resulted from such temperature and pressure changes in other rock-water systems. This was experienced at the Rocky Mountain Arsenal near Denver, Colo. (Hoover and Dietrich, 1969; Healy and others, 1968).

Snow (1968) described fracture deformation and changes in permeability and storage upon change in fluid pressure. Pickett (1968) described fractured rocks and the relation of these properties to the earthquakes at Derby, Colo., and Birch (1958) described some results of temperature changes in deep systems.

As a result of research still in progress at the Rangely oil field in Colorado, preliminary data indicate that seismic activity can be both induced and then reduced by changing fluid pressures in some deep rock-water systems (Raleigh and others, 1971).

Little or no seismic activity is anticipated in the Imperial Valley area in response to pumping from the unconsolidated aquifers to depths of several thousand feet. The threat of earthquakes being induced by deep fluid withdrawals or injections, particularly if large stress differentials are produced and consolidated formations are involved, must be considered a definite possibility. Apparently no significant earthquakes have been reported at the heavily developed Wairakei, New Zealand, geothermal field (Hunt, 1970).

In summary, it must be anticipated that large-scale water production from deep high-temperature fractured rocks of the Salton Trough geothermal system or high-pressure injection of fluids, or both, might constitute a seismic hazard. Extensive research will be needed to determine the extent of the hazard and the operating procedures that would reduce or overcome the possibility of any such induced seismic activity.

AIR, WATER, AND NOISE POLLUTION

Air, water, or noise pollution could result from production of water and steam from the

Salton Trough hydrothermal system unless adequate engineering is provided and effective production practices are invoked to prevent such pollution. Of the three hazards, the water-pollution potential is the best known; Federal, State, and local regulations adequately control the operating procedures and practices that are permissible. Proper practices should make it possible to prevent water pollution in the area. However, prevention of water pollution will materially add to production costs and consequently may affect the economic feasibility of development programs.

Air pollution might possibly take two forms (1) an increased humidity burden caused by releasing vapor to the atmosphere, or (2) release of mineral vapor and gases to the atmosphere. Because evapotranspiration associated with irrigation in the area exceeds 3 million acre-feet annually, the moisture burden that could be expected to result from geothermal power production probably would be below expected natural variations in the humidity. Therefore, the increased humidity burden probably will not constitute a hazard. Detailed engineering estimates should be compiled, however, to confirm this preliminary conclusion.

Serious air pollution might result from noxious gases, such as hydrogen sulfide, and mineral vapors if these are released to the atmosphere with steam. Mercury vapor may constitute a hazard. Barnes (1970) described anomalous waters from much of the Pacific margin of the United States and included water from the Wister mudpots near Salton Sea. He attributed the anomalous waters to deep metamorphism of marine sedimentary deposits and pointed out their association with mercury ores. Because marine rocks are almost certainly present in the deepest part of the Salton Trough and thus are being metamorphosed, detailed analyses should be made of steam produced before large-scale release of vapors to the atmosphere during tests and production. If mercury vapor is detected, the concentration and hazard should be determined.

Noise is produced at high levels during geothermal production. Experiments for noise reduction should be carried out to provide engineering designs to keep noises to environmentally acceptable levels.

ADDITIONAL DATA NEEDS

Many private and public agencies have worked, drilled, and tested to provide data needed to determine the magnitude of the water and geothermal-power resources of the area and its quality. Still a paucity of data exists.

Although the lack of existing data is a serious problem, an equally serious one is encountered by all workers who seek to study the system. The available data that have been accumulated over the years are in files of numerous public agencies, private individuals, and commercial firms. These data, for the most part, are unorganized and in various formats. The lack of a systematic tabulation of the data and an analysis of the accuracy and usability of the data is at present the greatest handicap to effective study of the hydrothermal system. An analysis and systematic tabulation of all the available data should be given a high priority as additional studies are planned.

Available data from wells in the Imperial Valley area are mainly from deep test wells drilled during exploration for oil or high-temperature water and steam. For these wells few data have been obtained at shallow and intermediate depth as drilling progressed. This results in a gap in our knowledge of the vertical variation in temperature and pressure in the shallow zones. It also leaves a gap in geologic data relative to permeability and porosity of the rocks and deposits, and type, distribution, and extent of cementation or other chemical or physical alteration of the original deposits.

Data from some recently drilled shallow test wells partly compensate for this general lack of data for shallow zones, but even these holes have not provided all the data needed. Few of these shallow wells have been drilled on the margins of the high heat-flow anomalies where temperatures decrease rapidly and chemical cementation presumably occurs. Data on pressure (or head), temperature, cementation, porosity, permeability, and water quality in such areas would prove useful in achieving a full understanding of the hydrothermal elements and mechanisms.

Data of the type needed for accurately estimating rock porosity and permeability are almost completely lacking. Insofar as can be determined, only well 92 (U.S. Bur. Reclamation 127) has both a gamma-gamma log and a neutron log. This combination of logs provides the most dependable means of estimating porosity and permeability of the deposits. Future research would be greatly enhanced if such logs were provided for all new deep and shallow wells drilled.

Water-quality data and water-level measurements in wells 1,000–3,000 feet deep are scarce; for deeper test wells they are virtually lacking. In fact, preproduction water-level altitudes in deep wells are not commonly recorded. Such data would be very useful.

Many additional water-quality data are needed to adequately define the system. Of particular importance, oxygen and hydrogen isotope data should be obtained routinely for all water sources until the three-dimensional distribution of water from the Colorado River and local soucres is clearly defined. Oxygen isotope data should also be obtained for the reservoir rocks penetrated in test wells.

Many additional geologic data will be needed if a clear understanding of the hydrothermal system is ever to be obtained. Accurate data on three-dimensional distribution of porosity, permeability, and thickness will be particularly important if quantitative predictions are to be made of the effects of proposed development.

The ground-water recharge-discharge relations have not yet been determined with sufficient accuracy to predict the possible system changes that might result from large-scale water production. Rates and areal variations of water losses from the canals should be determined. A better understanding of rates and areal distribution of ground-water discharge to the drainage canals should be obtained.

Subsidence resulting from ground-water developments in Imperial Valley could be a limiting restraint. Long before actual withdrawals occur, a surveillance program should be implemented to monitor fluid-pressure and land-surface changes that might take place. Also consideration should be given to a measuring program to differentiate tectonic changes and surficial compaction of shallow deposits resulting from the effects of ground-water production.

A complete analysis of the data-collection program needed for planning, developing, and eventually operating a large-scale water-production program in the Imperial Valley area is beyond the scope of this report. Needless to say, such comprehensive plans would require decisions by management that could only be based on a much more accurate and extensive knowledge of the system than now exists. Therefore, as plans for development of the water resources progress, the need for data will increase. The types and kinds of data that will be needed must be determined in advance of need, accuracy standards for the data must be established, and the program must be timed to provide the data as they are needed.

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