Geothermal Rm.

-1972-
FIRST CONFERENCE OF THE
GEOTHERMAL RESOURCES CONCIL
EL CENTRO, CAL.

COOPERATIVE GEOLOGICAL-GEOPHYSICAL-GEOCHEMICAL INVESTIGATIONS OF GEOTHERMAL RESOURCES IN THE IMPERIAL VALLEY

by

Robert W. Rex*

Introduction

The Imperial Valley is a major rift valley characterized by unusually high heat flow and large quantities of water in storage in the thick fill of alluvium provided by the sediments of the delta of the Colorado River. The geology and geophysics of this valley with applications to its geothermal potential is under study by the staff of the Geothermal Resources Program of the Institute of Geophysics and Planetary Physics at U.C. Riverside. The inventory of hot water appears to be sufficiently large that if used for water desalination it might add several million acre-feet of new water to the resources of the lower Colorado River basin. This distilled water would serve to lower river salinity and provide extra water to help meet the U.S.-Mexico treaty commitments. A major fraction of water desalination costs lie in the cost of energy and are related to desalination technology which is directly related to water chemistry. The discovery of low salinity geothermal waters in the Imperial Valley opened the possibility for a major breakthrough in lowered water desalination costs. The key step in evaluating this potential is the location of a geothermal prospect in a technologically and environmentally acceptable area. The work reported here encompasses a description of such an area which we have called the "Mesa" anomaly.

We have tried to develop a broad understanding of the origins of the waters of the Imperial Valley and how natural recharge occurs. We have started studies of faults to assist in engineering planning to assist in detecting possible hazards. We have been studying the structural and stratigraphic geology of the basin to know where sands and shales can be expected. We have studied the patterns of heat flow and are utilizing a wide range of geophysical techniques including gravity, heat flow, seismic, and electrical methods to develop a three dimensional understanding of the geology and hydrology of the Imperial Valley. This understanding is essential for prudent development and management of the geothermal resources without negative environmental consequences.

This document reports the results of the third year of our U.C.R. investigations in Fiscal Year 1970-71 and represents only the beginnings of what can and should be a long range continuing program.

Results

1. A primary result reported here is that the "Mesa" geothermal anomaly, previously discovered by R. W. Rex, is large, and has a clearly coincident thermal, gravity, and electrical resistivity anomaly.

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2. The stratigraphic section for the proposed geothermal test well at the "Mesa" anomaly would be entirely sedimentary, consisting primarily of sand bodies, and massive porosity exists to at least 10,000 feet indicating that a geothermal field if developed at the Mesa anomaly would be producing from an extensive water saturated sand reservoir.

3. The waters in the overall East Mesa area are very low salinity ranging from nearly fresh water in the southeast to salinities close to half that of sea water on its western margin.

4. The chemical composition of the waters of the central portion of Imperial Valley basin waters is not that of current surface flow of the rivers but has closest affinities to the underflow coming into the valley although marine sediments appear to occur on basement on West Mesa and on basement to the east in Arizona south of Yuma.

   Low salinity waters dominate the basin hydrology and waters as saline or more saline than sea water appear to be restricted to the immediate area of the Salton Sea.

5. Mountain runoff waters can be distinguished in the subsurface by their relatively lower salinity and high bicarbonate concentration, and their heavy isotopic composition. These mountain runoff waters move west across East Mesa. The local hydrology requires that this precipitation originates in the Chocolate Mountain watershed area. This conclusion is important because it indicates that the various north-south faults do not act as serious barriers to natural groundwater flow. This means that waters artifically introduced along the eastern margin of the basin may be expected to penetrate westward across the various faults. This would mean that pressure maintenance for much of the basin might be possible from only a limited number of reinjection or percolation sites, if properly located. Further studies are required in this area.

6. Revised fluid reserve calculations based on additional porosity data continue to show that the low salinity water resources of the Imperial Valley may exceed two billion acre-feet.

7. Most Imperial Valley waters show a departure in their isotopic composition from the main sequence of present surface waters. This could be explained by large scale equilibration against hot rocks, partial non-equilibrium evaporation before percolation underground, or by a yet not recognized mechanism active in the Imperial Valley.

8. The close relationship between gravity highs of about 2 milligals originating in the sediments and the occurrence of rising plumes of hot water has been clearly demonstrated both at the "Dunes" and the "Mesa" anomalies.

9. Many of the faults which break the surface in the Imperial Valley are evident in infrared aerial photographs. Preliminary studies reported here suggest that a basin-wide study is likely to provide a substantial improvement in our knowledge of the location of this type of fault. The

Imperial fault which breaks the surface is known to be cold over a major portion of the surface break. These fault data are suggested to be useful for earthquake studies. We suggest that their relevance to geothermal resources mapping depends primarily on the degree to which future studies indicate that faults influence groundwater flow.

10. The oceanic plate tectonic model is modified in the Imperial Valley by the evidence of a series of complex blocks with the generation of both tensional and compressional features in the valley. Major strike slip faults dominate the tectonic fabric but conjugate features increase complexity by a large degree and a major amount of work would be needed before any geologically sound structural models could be generated. Approximately a hundred buried concrete benchmarks were emplaced to serve as a start on a ground displacement study.

11. Xenoliths within the obsidians at the volcanoes at the south end of the Salton Sea provide samples of the basement under the Imperial Valley. These xenoliths include partially remelted granitic rocks, fragments of basalt, greenschist, and baked shale and sandstone. This is taken as evidence that the basement in the valley consists in part of partially remelted granite. This would render basement plastic and readily deformed. The source of the heat is suggested to be derived from basalt that comes into the basement and deeper sediments from below. This upward movement of basalt along a spreading zone is the continental equivalent to a sea floor spreading area. In the continental case the insulating blanket of wet sediment retains the heat and appears to produce a major geothermal resource.

12. Both "Mesa" and "Dunes" have near surface mushroom cap shaped plumes of hot water. Initial testing should focus on drilling within the stem of the mushroom. "Mesa" is recommended to the Bureau of Reclamation as the site for a first test well.

Recommendations

The studies carried out this year show a study of the entire rift valley is needed if we are to understand the basin structure, stratigraphy, hydrology, and to appraise the geothermal resources. A major need exists for samples of rocks and fluids from both intermediate and great depths in the valley sediments.

The major unanswered question is the reserve of accessible heat in storage in the waters and rocks of the Imperial Valley. An answer to the question is essential for along term development planning if the geothermal resources of the basin are to be used for desalination purposes. The answers to these questions will best be provided by a series of stratigraphic test wells drilled to basement in representative areas of the valley.

Another of the major questions outstanding is whether there is large scale transfer of energy and chemicals from the lower crust or mantle into the basin from discrete local sources (i.e., hot jets) or if heat is transferred over wide areas from diffuse sources. Furthermore, there may be different heat transfer processes in the marginal shelf areas where the granitic crust is thicker compared to the center of the valley where spreading centers may be introducing hot basalt directly into the sediments. We have proposed that the "Buttes", "North

Brawley", and "Heber" anomalies might actually be short segments of spreading centers. This hypothesis needs to be tested by a variety of studies. Direct access to an active onshore spreading center offers a major research opportunity to study the mechanics and petrogenesis of spreading centers in the U.S.

Any future geothermal developments in the Imperial Valley will be strongly influenced by the degree of hydrologic continuity in the basin. Additional isotopic and chemical studies are needed to develop an understanding of the identity and characteristics of all the hydrologic elements in the basin.

REVIEW AND DISCUSSION OF GEOTHERMAL EXPLORATION TECHNIQUES

by

Dr. Jim Combs*

Abstract

Geothermal exploration is a combination of science and technology that attempts to find and delineate economic concentrations of geothermal energy. At present, such concentrations occur where elevated temperatures (150 to 370°C) are found in permeable rocks at depths less than three kilometers. The main objective of any investigation of a geothermal anomaly is to obtain information that can be used to evaluate the four main characteristics of a geothermal reservoir, i.e., to estimate the base temperature, size, permeability and to predict the physical state of the fluid (water or steam). It is concluded that thermal, electrical, geochemical and passive seismic methods of exploration can furnish data about these characteristics and are, therefore, the most useful and important in geothermal exploration. Results obtained on the Mesa geothermal anomaly of the Imperial Valley in Southern California are presented as an illustrative example. Surface geological, geochemical, and geophysical reconnaissance surveys can provide inferences about geothermal reservoirs; however, in the final analysis, the drill will speak the last word.

Introduction

Exploration should begin with basic data collection. One should review all of the available data from the literature after a prospect has been chosen. Equally important is the consideration of possible legal problems (zoning, leasing, taxation, etc.), the possible marketing of the resource, and the economics of the program. After this subject matter has been considered, one is prepared to begin the exploration program.

The variation of temperature with depth is known as the geothermal gradient. A geothermal anomaly exists wherever the increase of temperature per meter of depth is greater than normal. The normal increase in the geothermal gradient is from 2.5 to 3.0°C per 100 meters. The study of geothermal resources for purposes of utilization should be understood in terms of geothermal anomalies.

The first and main objective of the investigation of any geothermal anomaly is to obtain, as quickly as possible and at minimum cost, an evaluation of its capacity to produce geothermal energy. A good geothermal reservoir should possess three characteristics: (1.) elevated temperature, (2.) storage capacity and (3.) fluid permeability.

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The characteristic base temperature of a reservoir (Bodvarsson, 1970) is particularly significant. Most geothermal power plants are designed to operate at pressures of about 5 kg/cm^2 absolute. Lower pressures necessitate larger turbines for the same capacity which results in lower utilization of energy and higher cost per unit of installed capacity. A total pressure of 5 kg/cm^2 is the saturation pressure of steam at a temperature of 150°C; consequently, a geothermal reservoir has little present value if its base temperature is less than 150°C. However, a geothermal reservoir becomes increasingly attractive at higher temperatures, especially temperatures above 200°C.

The size of a reservoir and its base temperature determine the magnitude of stored heat available for utilization; therefore, for a given base temperature and permeability, the larger the dimensions of a geothermal reservoir, the greater will be its capacity for producing geothermal energy.

The third important characteristic of a geothermal reservoir is the permeability of the reservoir rocks. This factor controls the productivity of individual steam wells and the proportion of stored heat that can be transferred efficiently to a power plant.

If other factors are equal, it is important to be able to distinguish vapor-dominated from hot-water systems (White, 1970; White, et al., 1971). A vapor-dominated system is preferable to a hot-water system. The former yields only vapor; whereas, the hot-water systems also produce much water (generally 70 to 90 percent of the total mass flow). This hot water is not utilized under present production techniques and may be a potential chemical and thermal pollution hazard. Deposition of SiO_2 and $CaCO_3$ may occur in well casings and surface pipes of some hot-water systems as well as in reservoir rocks of low permeability. Corrosion and erosion problems may range from insignificant to serious for both types of geothermal systems.

In the exploration for geothermal reservoirs, it is, therefore, desireable to use methods which are capable of providing information about these four characteristics, i.e., temperature, size, permeability and type of system. It is concluded that thermal, electrical, geochemical and passive seismic methods of exploration can furnish data on these characteristics and are, therefore, the most useful and important in geothermal exploration. Geothermal exploration should always be regarded as experimental because the character of hydrothermal systems varies so greatly from one field to the next. The problems associated with each must be approached individually and too great a reliance must not be placed on experience gained elsewhere.

The art of geothermal exploration is of recent origin. The great advances registered in exploration techniques have been due not only to research, but also to practical experiments. In the remainder of the paper, geological, geochemical and geophysical techniques will be reviewed and discussed. Results of the geophysical exploration of the Mesa geothermal anomaly of the Imperial Valley of southern California will be presented as an illustrative example. Throughout this discussion as well as when one is prospecting, one should always remember that the results obtained by any single method are not conclusive, and it is to ones advantage to utilize a number of complementary methods.

Geological Considerations

It is evident that geothermal resources are restricted to certain places and particular areas of the earth's crust. McNitt (1970) has written a summary on the geologic environment of geothermal fields as a guide to exploration. The following regional geological conditions are indicative of most geothermal systems with potential energy production: 1.) Late Tertiary and Quaternary volcanism, 2.) recent tectonism, and 3.) areas of high temperature and, consequently, greater-than normal heat flow (Lee and Uyeda, 1965; Oxburgh and Turcotte, 1970; Wunderlish, 1970; Tamrazyan, 1970).

At the commencement of any exploration, it is likely in many cases that information is already available from regional surveys, for example, topographical, hydrological, geological and/or geophysical surveys. These regional surveys may greatly assist the interpretation of local phenomena.

Just as petroleum exploration, in its initial stages, took as points of departure the existence of oil seeps, and wells were sited near these seeps in order to pinpoint the deposit in the subsurface; and just as, in many aspects of mining exploration, the existence of gossans, hardpans, etc., was used as the basis for drilling for an economic deposit, so, equally, geothermal exploration has had its beginning in drilling surface manifestations. However, the conclusion was soon reached that the existence of these surface manifestations (geysers, fumaroles, hot springs, mudpots, deposits of sinter, travertine or other hydrothermal activity) in an area indicates the existence of geothermal resources in the subsurface, but does not necessarily indicate the best place for siting wells.

Generally, it may be said that it is essential to commence by delimiting the thermal area geographically. Geological mapping, together with general and detailed reconnaissance, is then pursued in the thermal areas and in the surrounding zones. The use of aerial photographs and other information should be used before starting the geological work on the surface. Field work should be done by small, versatile parties, using aerial photograpshs as a basis for mapping. Geologists should note the structural setting, volcanic associations, possible aquifers, permeability of the rocks, alignment of fumaroles or hot springs along faults, and other such phenomena.

As part of the surface reconnaissance, one should not ignore such things as vegetation. Since certain types of vegetation are modified in a characteristic way be various temperatures, vegetation may be an indicator of thermal areas.

In summary, from the geological field work, one should proceed to interpret the observations to obtain a structural, stratigraphic and petrological picture that is as realistic as possible.

Geochemical Techniques

Both chemical and isotopic techniques have proven useful for geothermal exploration. The geochemical approach likely to be of most use for preliminary evaluation of an unexplored area is an inventory of thermal springs and fumaroles. The temperature, rates of discharge (measured or estimated), and chloride content should be established. The gas in the steam of emanations, as well as the condensed steam from hot waters should be sampled and analyzed. For background, rainwater, snow and large flowing water bodies should be sampled. Samples are easily taken, and the analytical work should not be costly.

Ellis and Mahon (1964) and Ellis (1967) demonstrated in their classic experimental studies on water-rock interactions that concentrations of the major rock forming elements in waters are controlled largely be temperature dependent reactions. Geochemistry is especially useful for predicting subsurface temperatures of hot-water systems (Arnorsson, 1970a, 1970b; Ellis, 1970; Fournier and Truesdell, 1970; Fournier and Truesdell, 1971; Koga, 1970, Mahon, 1970; Mercado, 1970; White, 1970). Evidence from surface hot springs will commonly, but will not always, permit a preliminary evaluation of a geothermal system as favorable or unfavorable.

The basic principle of all chemical techniques is that the chemical composition of groundwater, hot springs, or well water being sampled is indicative of the base temperature of the geothermal reservoir. The following assumptions must be made:

1.) Chemical equilibrium between the ionic species in the fluid and the rock is attained in the geothermal system.

2.) As the geothermal fluid flows to the surface, the chemical composition of the indicator ions is not decreased by significant chemical precipitation. This, in general, requires rapid transit of fluid from the reservoir to the sampling point.

3.) For some chemical indicators, e.g., SiO_2, it is required that the geothermal fluid not be diluted by groundwater. For others, such as Na/K, it is only required that a diluting groundwater have a chemical composition so low that the chemical ratio is insignificantly modified.

As can be seen, the inaccuracy of these assumptions can make interpretation of chemical indicators difficult.

The chemical indicators which have been used most extensively are SiO_2 and Na/K. The silica content has been the best indicator with the Na/K ratio the next most useful. Fournier and Truesdell (1971) apply a correction to the Na/K ratio using Ca which considerably improves their predicted base temperatures. Other indicators such as sinter deposits, Mg/Ca, and H_2/other gases ratios have been used. White (1970) has provided an excellent review of geochemical techniques.

Stable isotope techniques involving hydrogen, oxygen and carbon provide two types of information. First, they can be used to indicate the presence of a geothermal system, that is, the isotopic composition of waters from thermal springs and wells can be used to determine whether there has been enrichment or fractionation that can be related to temperatures at depth. Secondly, they can be used as geothermometers.

The oxygen and hydrogen isotopic composition from any locality are related by a well known equation (Craig, 1961). The isotopic composition of precipitation for a particular locality is relatively constant when averaged over yearly periods. Since the quantity of hydrogen in groundwater is much greater than the quantity of hydrogen in rocks, the hydrogen isotopic composition of precipitation is not changed as it flows through a geothermal system. However, the quantity of oxygen in rocks is of the same order of magnitude as the oxygen in groundwater. Thus, the oxygen isotopic composition of groundwater can be changed if oxygen isotope exchange occurs. Clayton, Muffler and White (1968) have observed that the minimum temperature for oxygen exchange is

150°C. Geothermal brine, which is 5-10% of a hot spring water or well water, may be detected in groundwater because of the increase of O^{18} in the sample caused by the high temperatures in the geothermal system.

Reliable indicators of subsurface temperature for the vapor-dominated systems are lacking. The isotopic ratio of C^{13}/C^{12} may offer the most hopeful approach (Craig, 1963; Ferrara, et al., 1963; Hulston and McCabe, 1962). The indicated isotope temperatures are usually near or above the observed reservoir temperatures.

Finally, it should be pointed out that both chemical and isotopic studies have their advantages and disadvantages. One should not be replaced by the other. Both should be used. Both are inexpensive relative to other geothermal exploration techniques.

Geophysical Techniques

The conditions indicating the existence in the subsurface of a reservoir favorable to the commerical accumulation of steam necessitate the use of various physical parameters of the rock. In certain respects, the geophysical exploration used here resembles that utilized in prospecting for hydrocarbons. One must, therefore, make use of certain parameters, such as temperature, electrical conductivity, velocity of propagation of elastic waves, density, magnetic susceptibility and radioactivity.

Surface temperatures, gradient measurements and heat flow determinations represent some of the longest established exploration methods and provide the most rapid and direct way of making a first estimate of the size and continuous power potential of a geothermal system. Excellent reviews of thermal techniques have been published by Thompson, et al., (1961), Beck (1965) and Dawson and Dickinson (1970).

The average world-wide conductive heat flow is about 1.5 HFU; 1 HFU = $1\mu cal/cm^2 sec$ (Lee and Uyeda, 1965; Simmons and Horai, 1968). Localized low intensity heat anomalies are produced in many ways, including exothermic chemical reactions, radioactivity, friction of fault movement, and migration of waters of different origin in areas of nearly normal geothermal gradient. Heat flows caused by such phenomena are usually of restricted extent and of limited duration. However, the high intensity areas require transfer of heat on such a scale that magmatic temperatures and magma reservoirs must be present nearby.

Along the volcanic belt in the North Island of New Zealand, Studt and Thompson (1969) find that the combined heat flow from the hydrothermal fields is equivalent to a mean heat flux (mostly convective transfer) of about 20 HFU. Other examples included the measurements by White (1957) near Steamboat Springs, Nevada which indicate heat fluxes 120 times normal or Yellowstone's Firehole geyser basins where an area of 700 km^2 has an average heat flow of at least 67 HFU (Fournier, et al., 1967).

An almost universal factor which must be taken into account when making or interpreting any shallow temperature or gradient survey, or shallow heat flow, is the possible effect of movement of shallow groundwater across the survey area. A relatively slow movement of groundwater (with a very slight temperature rise) can carry away the conductive heat flow from even a strong thermal anomaly. Surface temperature patterns can be displaced and gradient measurements in deeper holes can be made unreliable by movements in subsurface aquifers.

The usefulness of temperature and gradient measurements at depths of the order of 1 meter (Thompson, et al., 1964), although rapid and inexpensive, are usually not worthwhile. It is advisable to rely on a smaller number of deeper holes in which temperatures and gradients can be measured more accurately and with greater sensitivity.

Shallow (a few tens of meters) to intermediate (100 to 200 meters) depth boreholes may provide both thermal and chemical information. This geothermal exploration technique which uses thermocouples and thermistors to measure the temperatures as a function of depth has been utilized by a number of investigators (e.g., Burgassi, et al., 1964, 1970; Combs, 1971; Combs and Rex, 1971; Duprat, 1970; Lovering and Goode, 1963). In summary, the use of near surface temperature and gradient maps in exploration may provide good targets, but the quantitative estimation of temperatures at depth depends on a number of factors that may be poorly known. The detailed mechanisms of heat transfer in a geothermal system are not completely understood but conduction from a magma reservoir to a large system of convecting groundwater seems the most plausible (White, 1968).

Over the past few years, attempts have been made to detect or map thermal activity by means of the radiation emitted principally in the near or intermediate infrared (Friedman, et al., 1969; Gomez Vallee, et al., 1970; Hochstein and Dickinson, 1970; Hodder, 1970; Palmason, et al., 1970). Longer wavelength infrared emissive or reflective surveys are carried out by special scanning equipment which may be adopted for ground or airborne use. The infrared scanners normally operate in the 3 to 5 micron or 8 to 14 micron transmission windows in the atmosphere. Thermal infrared imagery at present is a noise limited system, that is, because of the 1.) differences of emissivity and/or thermal conductivity of surface materials and 2.) microclimatic factors, most of the "thermal" anomalies on imagery are outcrop, slope direction, slope magnitude, soil moisture, fog or condensation, difference in rock properties, vegetation, etc.. At present, because of the poor signal-to-noise ratio, heat flux anomalies less than about 100 to 150 times normal can not be accurately detected with thermal infrared techniques.

Of all the conventional geophysical tools, electrical resistivity surveys appear to be the most used and useful technique for geothermal exploration (Hatherton, et al., 1966; Keller, 1970; Lumb and MacDonald, 1970; Meidav, 1970; Risk, et al., 1970). Since the resistivity of the ground is primarily dependent on the effective porosity, temperature, and salinity of the interstitial water, electrical surveys may be used to map the distribution (depth, thickness, and areal extent) of hot and/or saline water. The apparent resistivity is extremely low (1 to 5 ohm meters) for hot, saline groundwater. Measurements of apparent resistivity by DC or commutated DC methods has become a standard technique for outlining geothermal systems. This method simply maps hot and/or saline (a cold, salty brine gives an enormous anomaly) conditions at the water table. Steam filled zones will not be characterized by resistivity lows, but surrounding hot water halos may be, and thus resistivity surveying under these circumstances may be directed toward mapping structure. Resistivity surveys are not specific, but tied in with other techniques, can be powerful. Their only advantage compared with temperature surveys is that of speed in easy terrain and possible lower costs. The interpretation of field data is definitely less straightforward.

Electromagnetic techniques, which have been utilized in geothermal exploration, include electromagnetic gun surveys (Lumb and MacDonald, 1970), audiofrequency magneto-telluric methods, and two-coil profiling methods. A review of various survey methods, theory, field methods, and results has been published by Keller (1970). His review covers both induction and direct current techniques and their applicability over a wide range of depths.

Seismic exploration methods are based on measurements of the velocity of propagation of elastic waves which are proportional to several constants and parameters, such as the modulus of elasticity, the density, and the modulus of incompressibility. Seismics can be subdivided into active methods and passive methods.

Active seismic methods use explosions to initiate elastic waves. Active seismic methods include reflection and refraction, depending on whether the energy reflected from the interfaces is used, or whether, on the other hand, the wave has passed through formations of different character, to emerge at the surface after travelling on a certain path. The active seismic methods are effective in detecting faulting, in revealing the subsurface geological structure and in determining the shape and depth of the basement.

Passive seismic methods record locally generated microearthquakes and thus disclose faults and earth movement activity which may be associated with geothermal systems. Microearthquakes believed to arise from fault movements concentrated in geothermal areas have been described by Lange and Westphal (1969) at The Geysers, California; by Ward, et al. (1969) in Iceland; by Brune and Allen (1967) in the Imperial Valley; and by Ward and Jacob (1971) at Ahuachapan, El Salvador. Microearthquakes will most likely prove to be a better monitoring tool than an exploration tool.

A variation of this method, called seismic noise detection or geothermal noise detection, records acoustic noise patterns within certain frequency ranges. Seismic noise measurements seem to provide a further very useful and relatively simple method for detecting and mapping certain types of geothermal areas (Clacy, 1968; Goforth, et al., 1972; Whiteford, 1970). Initial studies suggest that individual geothermal systems have characteristic seismic signatures. The data also suggest that there is an empirical relationship between a geothermal reservoir at depth, high temperature gradients, and high seismic noise level. If this relationship proves to be reliable, geothermal noise detection could be useful in future geothermal exploration due to the relative speed, mobility, and inexpensiveness of the seismic technique.

An important physical parameter is the density which is used in the gravitational method of prospecting. Density contrasts between rocks produce gravity anomalies that are extremely useful in delineating major structural features as well as local structural highs, buried volcanic or intrusive rocks, and areas of densification attributable to hydrothermal metamorphism. All of these features may point out the presence of a local heat source. Gravity is a powerful tool for delineating the geologic setting, but it is open to gross misinterpretation if not used in conjunction with other exploration techniques.

In general, magnetics and aeromagnetics are probably the least useful conventional geophysical tool as pertains to geothermal exploration. The original idea was that hydrothermal alteration would convert magnetite to pyrite, but so many factors influence the character of a magnetic map, that it is extremely difficult to interpret in terms of geothermal resources.

In summary, the most useful geophysical techniques seem to be temperature or gradient surveys, heat flow, electrical resistivity surveys, and possibly some passive seismic method such as seismic noise detection. Gravity and aeromagnetic work may be used to build up the regional geologic and tectonic setting, and active seismic profiles provide regional and local detail.

Case History: Mesa Geothermal Anomaly of the Imperial Valley, Southern California

Case histories of exploration for geothermal steam are few and incomplete. Unfortunately, this one is also incomplete, but will undoubtedly be useful. Until now most geothermal exploration has been directed primarily to areas of surface heat leakage. As was the case for petroleum exploration, one of the greatest challenges in geothermal exploration is the discovery of large exploitable heat reservoirs where there are no thermal manifestations (e.g., hot springs, fumaroles, or sinter deposits) at the surface. We feel that the Mesa geothermal anomaly located on the western edge of the East Mesa area of the Imperial Valley in Southern California (Figure 1) is such a phenomenon, that is, the Mesa anomaly is a large potential geothermal reservoir which has no surface thermal manifestations. The case history of this area is incomplete in that at present we only have geophysical data and sketchy geological data; unfortunately, we have no geochemical information.

The Mesa anomaly is on the east flank of the Salton structural trough. Seismic refraction profiling (Biehler, et al., 1964) indicates that granitic and metamorphic bedrock is at a depth of about 3.5 kilometers. Wildcat oil test wells have been drilled 5.8 km northeast and 4.5 km southeast of the proposed site. The H. W. Shafer "Barbara" 1 well was 2,444 meters deep while the American Petrofina No. 27-1 well was 3,238 meters deep. Electric logs of these wells show a sequence of clay and sand beds, with minor silt beds. Sand is predominant throughout the section.

Geophysical data were obtained through the following field surveys conducted during the period 1969-1971: (1) geothermal gradient measurements in approximately 50 test holes ranging in depth from 30 to 425 meters; (2) gravity measurements with station spacing ranging from several kilometers throughout much of the East Mesa area to about one-half kilometer spacing on the Mesa anomaly; (3) seismic noise survey of the Mesa anomaly with 1.5 kilometer spacing between observations; and (4) widely spaced D-C electrical resistivity soundings. All of these geophysical surveys will be examined in detail in future publications; therefore, I will include only a brief discussion of each of them in order to indicate how this type of information can be used in the siting of a geothermal test hole.

A D-C electrical resistivity survey was made of a large part of the Imperial Valley, including the Mesa anomaly (Figure 2). This survey was reconnaissance in character because of limited funds. However, the results show a 5 ohm meter closure enclosing the Mesa anomaly as defined by the other geophysical methods. The area included in the 5 ohm meter closure is approximately 50 square kilometers, and thus gives insufficient definition to site a deep test hole.

After removal of regional effects arising from basement and upper crustal rocks, the residual gravity map (Figure 3) shows a 4 milligal closure with

FIGURE 1.

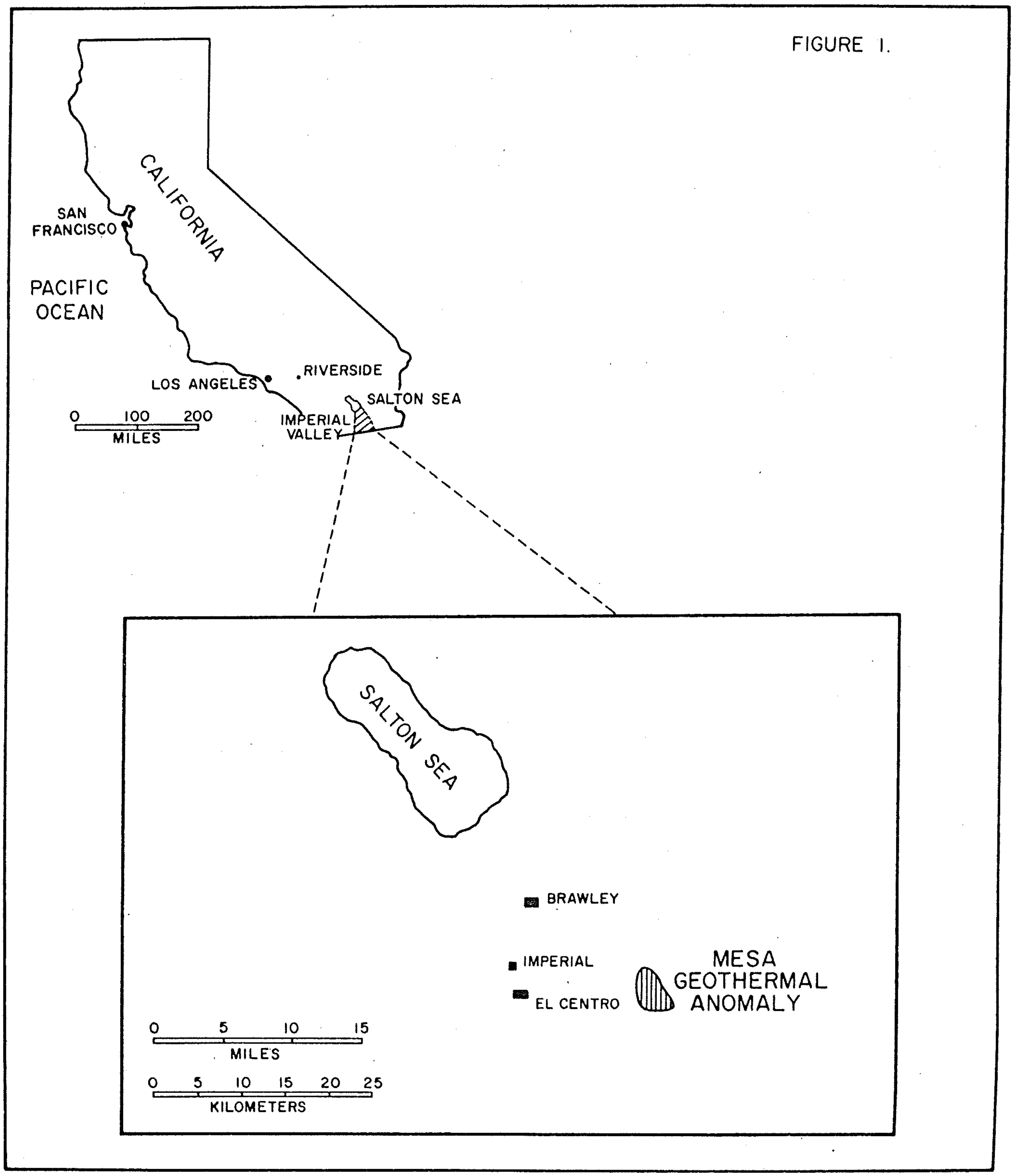
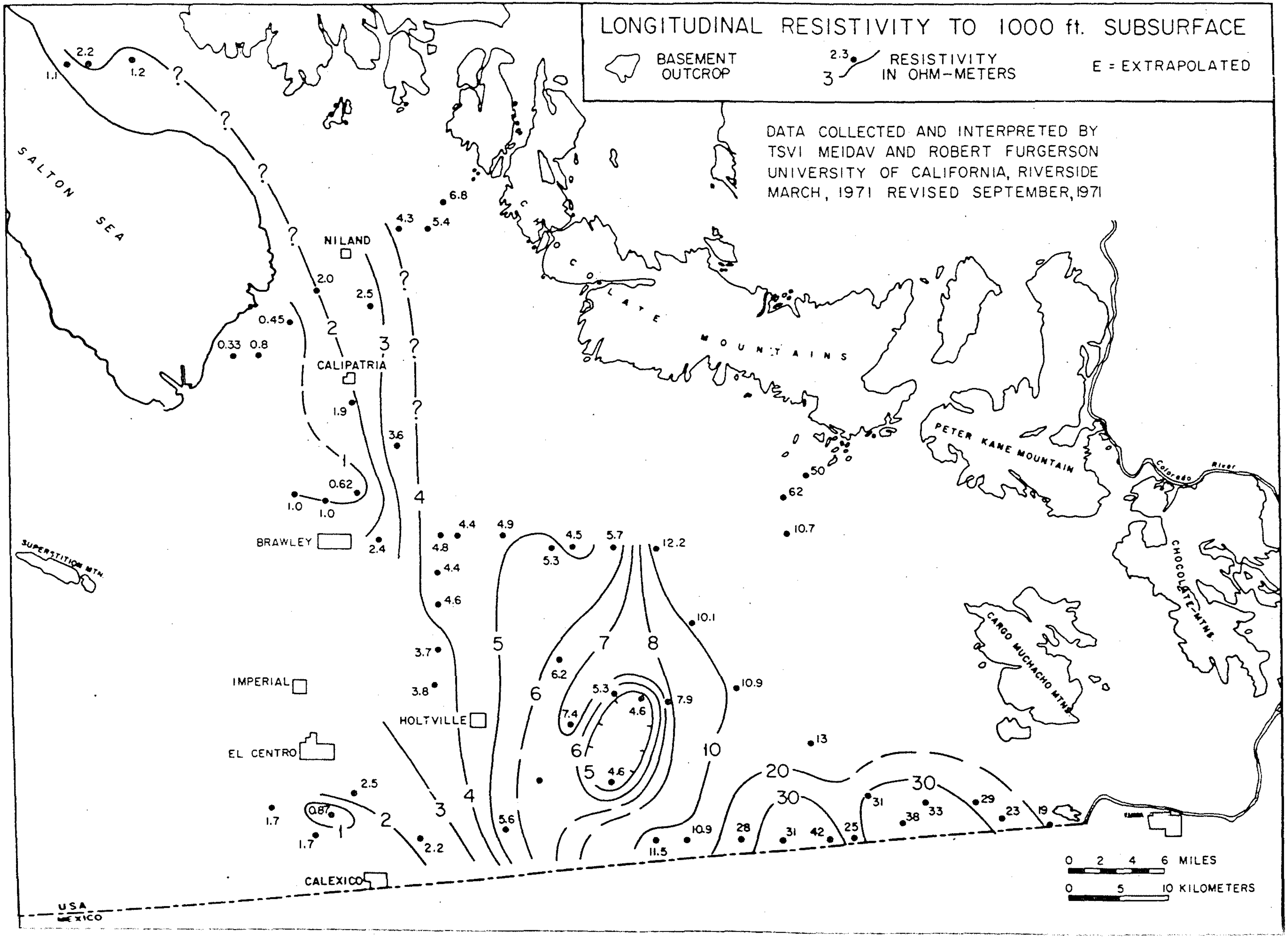

CALIFORNIA
SAN FRANCISCO
PACIFIC OCEAN
LOS ANGELES
RIVERSIDE
SALTON SEA
IMPERIAL VALLEY
0 100 200
MILES
SALTON SEA
BRAWLEY
IMPERIAL
EL CENTRO
MESA GEOTHERMAL ANOMALY
0 5 10 15
MILES
0 5 10 15 20 25
KILOMETERS

FIGURE 2.



LONGITUDINAL RESISTIVITY TO 1000 ft. SUBSURFACE

DATA COLLECTED AND INTERPRETED BY
TSVI MEIDAV AND ROBERT FURGERSON
UNIVERSITY OF CALIFORNIA, RIVERSIDE
MARCH, 1971 REVISED SEPTEMBER, 1971

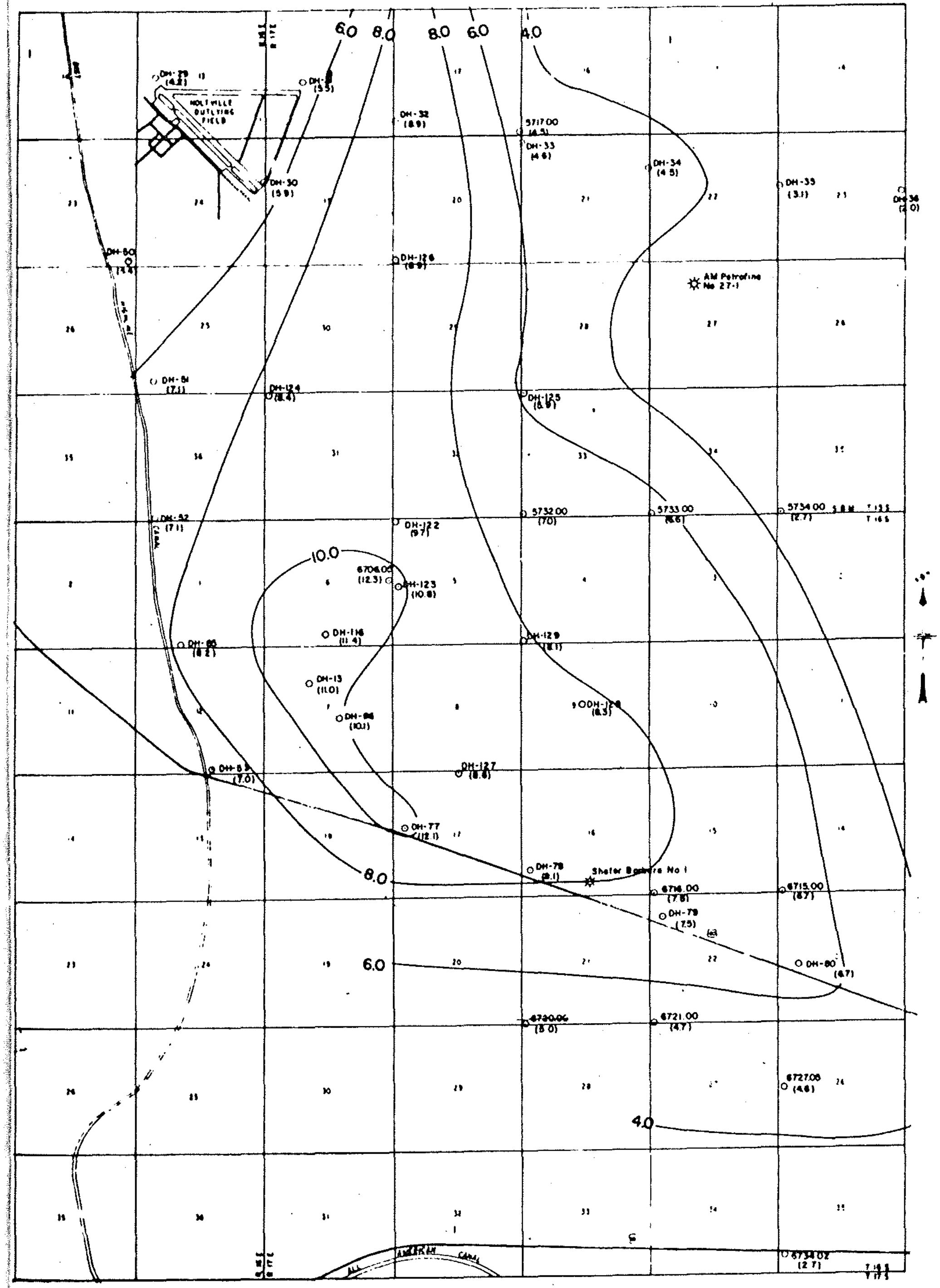


FIGURE 4
MESA ANOMALY GEOTHERMAL GRADIENT MAP

EXPLANATION

—8.0— Gradient in Degrees Fahrenheit Per 100 Feet

Contour Interval 2° Per 100 Feet

○ Thermal Drill Hole

☼ Wildcat Oil Test Hole

NOTE

Data Compiled and Interpreted by Jim Combs, University of California, Riverside, Sept 8 1971

SEPTEMBER 1971

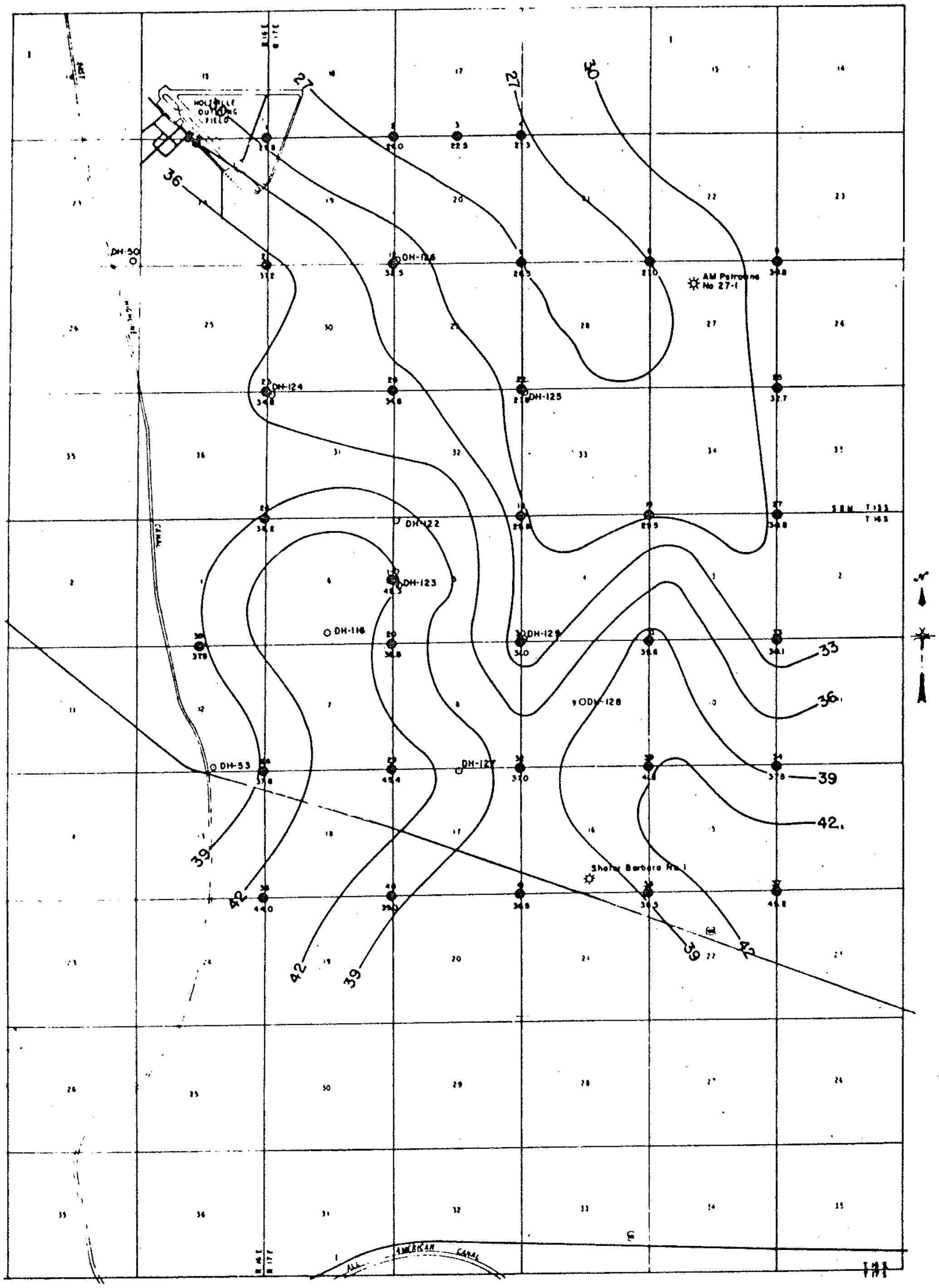


FIGURE 5.
MESA ANOMALY SEISMIC
GROUND NOISE

EXPLANATION

—42— Contours are given in Decibels (dB) relative to 1 (Millimicron per second)² per Hertz in the passband of 3.0 to 5.0 Hertz

NOTE

Data Compiled and Interpreted under the technical direction of E J Douze, Teledyne-Geotech, Dallas, Texas, August 1971

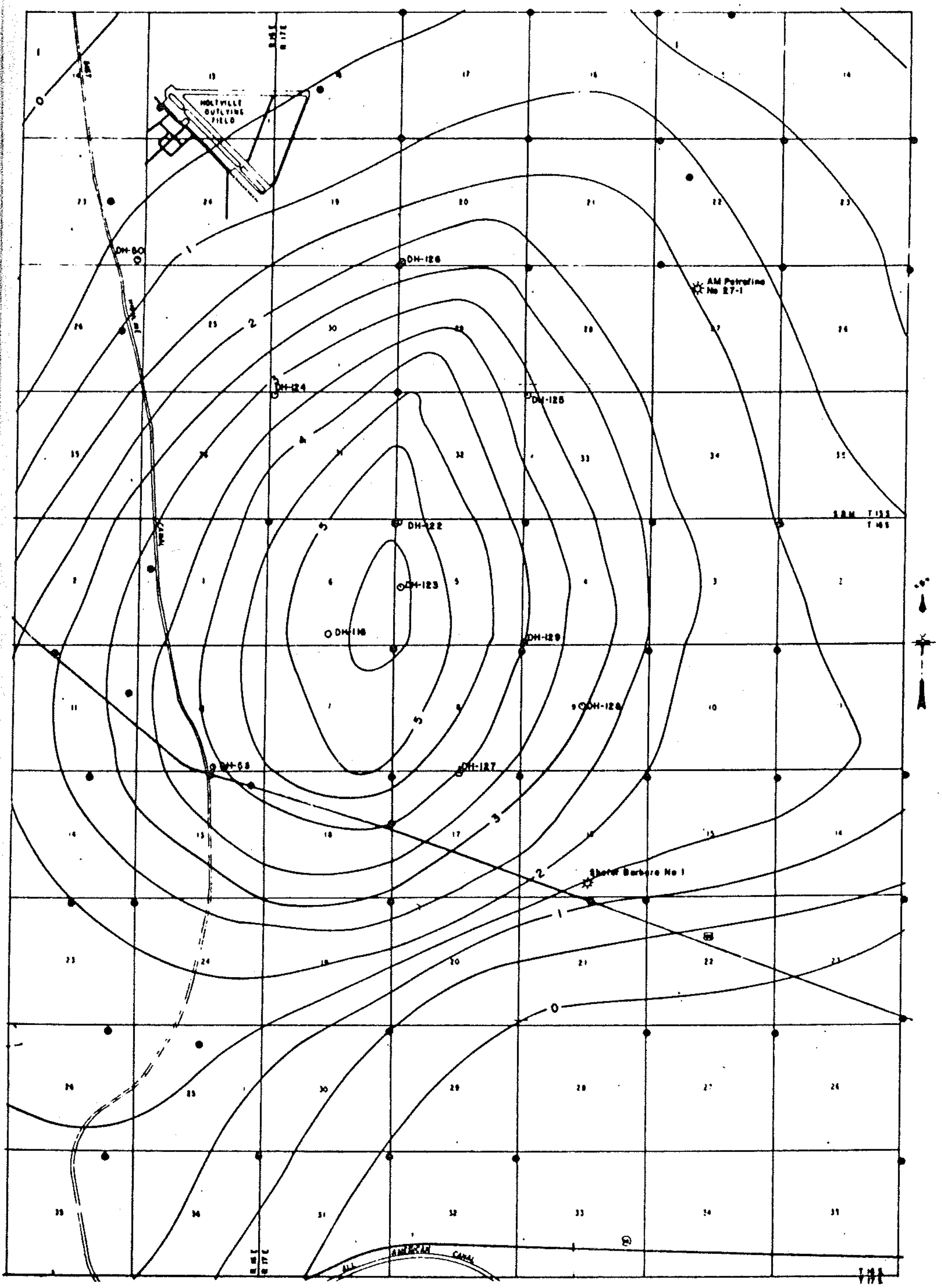


FIGURE 3.

MESA ANOMALY RESIDUAL GRAVITY MAP

EXPLANATION

—1— Gravity Contour in Milligals - Contour Interval 0.5 Milligal

○ Thermal Test Hole

☼ Wildcat Oil Test Hole

NOTE

Data Compiled and Interpreted by Dr Shawn Biehler, University of California, Riverside, Sept 1971

1000 0 2000 4000 6000 8000 10000

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KILOMETERS

SEPTEMBER 1971

its center encircling about 2.5 square kilometers in parts of Sections 5 and 6, T.16S., R.17E. This residual Bouguer anomaly indicates that a mass surplus exists under the area. The mass surplus could be explained by geothermal conditions which cause silica deposition, baking of clay sediments, and possibly low grade metamorphism.

Figure 4 is a geothermal gradient map showing increases in temperature with depth. Specially designed test holes were drilled to obtain the geothermal gradients. They were drilled by conventional rotary methods and completed with small diameter (1.9 to 5.1 cm) pipe, with a seal at the base. The pipe was cemented in place, filled with water, and capped. Temperature measurements were made with a thermistor probe. These measurements were repeated in each hole until thermal equilibrium was attained.

Temperature measurements were processed and evaluated to produce a map (Figure 4) showing the general shape of the upper part of the thermal feature at Mesa anomaly. It is suggested that the thermal feature in the SE ¼ of Sec. 6, T.16S., R.17E., may be a single manifestation of a deeper, substantially larger, convective hydrothermal system.

The results of a seismic ground noise survey conducted by Teledyne-Geotech of Dallas, Texas, is included as Figure 5. The map of this survey shows high ground noise in the southern and southeastern parts of the Mesa anomaly. According to Teledyne personnel, the ground noise map is contoured in terms of total power in the passband between 3.0 and 5.0 Hertz, which Teledyne converted to decibels (dB) of power using:

$$\text{Power (dB)} = 10 \log_{10} \text{(observed power)}$$

The original spectra from which these data were obtained are in units of millimicrons per second squared per Hertz. The physical relationship of this map to the foregoing geophysical maps is readily evident.

To summarize, in the area of the Mesa geothermal anomaly, the subsurface consists of a sequence of predominantly sandy deltaic sediments (Walter Randall, personal communication, 1971) at least 3.5 kilometers thick. Geothermal gradient measurements indicate high temperatures in the shallow subsurface. These thermal conditions are associated with a gravity high (which suggests metamorphism and/or mineralization caused by high temperatures), high seismic ground noise (probably caused by high temperature phenomena), and low resistivity values (caused by high temperatures and/or high salinity). From these geological and geophysical data, we have recommended that a deep geothermal test well be sited in the SW ¼ NE ¼ SE ¼, Sec. 6, T.16S., R.17E.

Conclusions

In an area scheduled for development, with little or no previous drilling information, the siting of exploration wells should be based on surface reconnaissance according to data of geophysics, geology, geochemistry, and hydrology. It should be paramount in ones mind that the results obtained by any single method are not conclusive and it is of immense advantage to make use of a number of complementary methods for geothermal exploration. It is concluded that thermal, electrical, geochemical and passive seismic methods of exploration can furnish data on the subsurface thermal processes and are, therefore, the most useful and important in geothermal exploration. Gravity and aeromagnetic surveys may be used to build up the regional geologic and tectonic setting. Active seismic profiles provide both regional and local detail.

The preliminary objectives will be to drill test wells to confirm the inferences from the surface reconnaissance surveys, and then to supply detailed information about the formations encountered, including their most important physical properties (porosity, permeability, and density) and the existing physical conditions, for example, the temperature and pressure of the fluids and the nature of the percolating fluids. As information from the initial drill holes is obtained, preliminary cross sections and temperature profiles should be drawn as a guide for subsequent siting of discovery wells.

In conclusion, the exploration results obtained from a single geological, geochemical or geophysical method are not conclusive, and it is of advantage to utilize a number of complementary methods; however, in the final analysis, the drill will speak the last word.

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