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PROPOSED SCIENTIFIC ACTIVITIES FOR THE SALTON SEA SCIENTIFIC DRILLING PROJECT

A Report of

THE EXPERIMENTS PANEL

Organized by
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ABSTRACT

The Salton Sea Scientific Drilling Project (SSSDP) has been organized for the purpose of investigating a hydrothermal system at depths and temperatures greater than has been done before. Plans are to deepen an existing well or to drill a new well for research purposes for which temperatures of 300°C will be reached at a depth of less than 3.7 km and then deepen that well a further 1.8 km.

This report recounts the Congressional history of the appropriation to drill the hole and other history through March 1984, gives a review of the literature on the Salton Sea Geothermal Field and its relationship to other geothermal systems of the Salton Trough, and describes a comprehensive series of investigations that have been proposed either in the well or in conjection with the SSSDP. Investigations in geophysics, geochemistry and petrology, tectonics and rock mechanics, and geohydrology are given. A tabulation is given of current commercial and state-of-the-art downhole tools and their pressure, temperature, and minimum hole size limitations.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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The drilling rig on the cover is reproduced from a photograph taken on location by Dan Lubian of a Republic Geothermal project in Imperial Valley. We wish to thank Republic Geothermal Inc. for the use of this photograph and their kind assistance.

1. INTRODUCTION

The Salton Sea Scientific Drilling Project (SSSDP) has been organized for the purpose of investigating a hydrothermal system at depths and temperatures depths greater than has ever been possible before. The initial plan was to deepen a 12,000 ft (3.7 km) commercial well in the Salton Sea Geothermal Field (SSGF) to 18,000 ft (5.5 km) in 1984, and make the well available for scientific purposes. Other options are now under consideration. The objective of this report is to describe the geologic background as well as a comprehensive series of investigations that have been proposed to take maximum advantage of this unique opportunity.

This report has been written primarily for agency planners and potential investigators who plan to participate in the project. A review of some of the background literature on the SSGF and its relationship to other geothermal systems of the Salton Trough is included. This has been taken from a more comprehensive report by Elders and Cohen (1983).

The report was prepared by an Experiments Panel of SSSDP that was organized at the request of O. L. Anderson, Director of the Institute of Geophysics and Planetary Physics, University of California. P. A. Witherspoon served as Chair and T.-C. Lee served as Secretary of the Experiments Panel. The Panel was organized into five Sub-Panels in order to address the following fields of interest: geophysics, geochemistry and petrology, tectonics and rock mechanics, geohydrology, and engineering development.

The membership of each Sub-Panel was as follows:

(1) Geophysics: T. Henyey, Chair, N. E. Goldstein, P. W. Kasameyer, T.-C. Lee, T. V. McEvilly, H. F. Morrison, J. E. Rawley, P. M. Wright;

(2) Geochemistry and Petrology: L. H. Cohen, Chair, R. O. Fournier, H. Staudigel;

(3) Tectonics and Rock Mechanics: T. Doe, Chair, O. L. Anderson, T. Dey, M. S. King, L. R. Myer, R. Richardson;

(4) Geohydrology: G. S. Bodvarsson, Chair, S. M. Benson, T. W. Doe, P.W. Kasameyer, T.-C. Lee, H. Murphy, H. J. Ramey, L. W. Younker;

(5) Engineering Development Requirements: R. J. Kelsey, Chair, S. M. Benson, W. D. Daily, B. R. Dennis, M. Hood.

1.1 GEOTHERMAL SYSTEMS OF THE SALTON TROUGH

1.1.1 Regional Setting

The Salton Sea Geothermal Field (SSGF) is one of a number of high-intensity geothermal fields which occur in a structural depression, known as the Salton Trough, at the head of the Gulf of California in northern Baja California, Mexico, and southern California, U.S.A. (Figure 1-1). This depression forms part of the boundary between the North American and Pacific plates. This region marks the transition between the purely extensional tectonics of the East Pacific Rise to the south, at the mouth of the Gulf, and the transform fault tectonics of the San Andreas Fault system, to the north. The SSGF thus represents one of the few places in the world where an extensional plate boundary is affecting continental crust (Elders et al., 1972; Elders and Biehler, 1975). The Salton Trough is a sediment-filled rift valley that represents the landward extension of the Gulf of California into North America. The high heat flow of this tectonic setting is the ultimate origin of the geothermal resources of the Salton Trough. This association and its relationship to the SSGF have been reviewed in considerable detail by Elders and Cohen (1983).

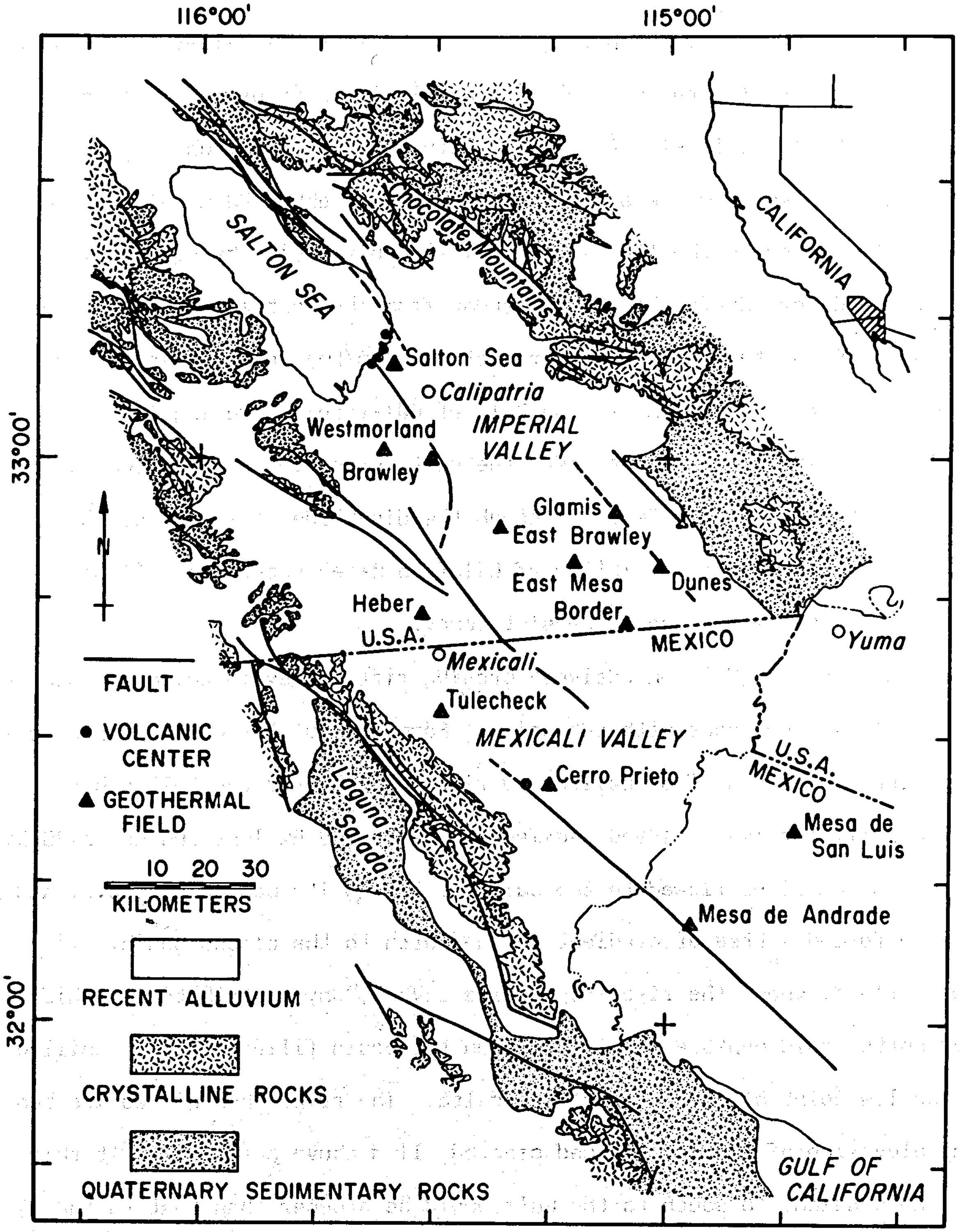

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Figure 1-1. Geothermal Fields of the Salton Trough.
Source: Elders and Cohen (1983).

The present apex of the Colorado River delta forms a low divide (11 m above sea level at its lowest point) between the Imperial Valley to the north and the Mexicali Valley to the south (Figure 1-1). Most of the Imperial Valley lies below sea level. At its northern end is the Salton Sea, which covers about 930 km^2 and has a surface elevation of about 70 m below sea level. Water entering the Imperial Valley can only escape by evaporation. The Colorado River enters the Salton Trough from the east at Yuma, 43 m above sea level. The delta slopes northward (at ~ 0.8 m/km) into the Salton Basin and southward (at 0.35 m/km) to the Gulf of California. During 1905 to 1907, the Colorado River flooded over the delta crest into the Salton Basin, forming the present Salton Sea. Although the discharge of the River is now into the Gulf of California, inflow of Colorado River water via irrigation canals causes the Salton Sea to persist today.

The Salton Trough is an actively growing rift valley in which sedimentation has almost kept pace with tectonism. Formation of the delta perpendicular to the length of the Gulf of California rift has isolated the Salton Basin from the Gulf, forming a closed sedimentary basin 200 km long and up to 90 km wide. When the river flowed to the Gulf, it graded its bed to sea level and therefore formed a steeper gradient to the north to the closed basin. In times of flood, when the river topped its levees, any distributaries which flowed north could capture the flow. Then the basin filled until it spilled over the low point of the crest of the delta. The river then graded its bed to the elevation of the lake it had created, 11 m above sea level. At this point the gradient to south to the Gulf would be steeper than that to the north so that, in times of flood when the river topped its levees, the distributaries which flowed south captured the flow. Thus the delta oscillated between two metastable conditions with the river flowing alternately to the north and south. The history of the Salton Basin during the last few million years has thus been cycles of filling with freshwater lakes followed by desiccation. ALthough sediments from the walls of the Basin form marginal alluvial fans, the Colorado River has dominated the sedimentary history.

1.1.2 Hydrothermal Systems in the Salton Trough

The Gulf of California and the Salton Trough are characterized by high regional heat flow. The deep basins within the Gulf geothermal anomalies can exhibit very high heat flow values, as high as 2.1 W/m^2 (50×10^{-6} cal $cm^{-2}s^{-1}$). On land more than a dozen geothermal anomalies have been recognized. These anomalies include the Salton Sea, Westmoreland, East Brawley, Brawley, Heber, East Mesa, Dunes, Glamis, and Border geothermal fields in the Imperial Valley, and the Cerro Prieto, Tulecheck, Panga de Abajo, Mesa de Andrade, Mesa de San Luis, and Desierto de Altar geothermal fields of the Mexicali Valley (Figure 1-1).

One feature of these geothermal fields is that they usually lack surface discharge or any other kind of surface expression even though they can have temperatures as high as 370 C at 1,800 m depth. Only the Salton Sea and Cerro Prieto fields have any surface manifestations such as hot springs and fumaroles. Those two fields are also the only ones associated with Quaternary volcanoes. The remainder have been accidently discovered during the drilling of (dry) oil wells or by geophysicsl surveys using gravity, thermal gradient, or electrical resistivity measurements. The high thermal gradients, which are related to circulation of convecting hot groundwater in the thick sedimentary fill, coincide with low-amplitude, positive, residual-gravity anomalies with closures of 2 to 20 mgals (Elders et al., 1972).

The chief exploration strategy used to discover and assess these "blind" geothermal systems was to measure heat flow in shallow boreholes drilled on positive gravity anomalies. The positive gravity anomalies associated with the thermal anomalies reflect (1) the presence of shallow, dense igneous intrusions; and/or (2) the increased density of sediments due to hydrothermal alteration. Both are encountered in boreholes.

Based upon study of cuttings and cores recovered, the most pervasive source of excess mass, at least down to the level penetrated by drilling, is the hydrothermal alteration of sediments. For example, intense metamorphism of the sedimentary fill occurs in the SSGF. Active formation of greenschist facies rocks is occurring at depths of 1 to 2.5 km below the surface, where the temperature ranges up to 365 C at 2 km depth (Muffler and White, 1968; McDowell and Elders, 1979). Brines recovered from these depths contain up to 25 wt percent of total dissolved solids (TDS) (Helgeson, 1968).

Although similar geothermal gradients are encountered in the Cerro Prieto geothermal field, the brine is much less saline. Typically the brine contains only 13,000-15,000 ppm of Cl, 7,000-8,000 ppm of Na, 500-600 ppm of Ca, and 1,500-2,000 ppm of K. The hydrothermal minerals encountered are similar to those seen in the Salton Sea field, but the degree of recrystallization is less intense. In both of these geothermal fields hydrothermal alteration affects the physical properties of the sediments by reducing porosity and increasing density. A transition in the nature of the permeability in these reservoirs therefore occurs - from matrix porosity in the upper part of the reservoir to fracture-dominated permeability at depth (Elders, 1979).

The Brawley and East Brawley geothermal fields appear to have temperatures and salinities intermediate to those of the Salton Sea field and the other identified geothermal fields of the Salton Trough. Temperatures in excess of 300 C and salinities of 200,000 ppm TDS have been encountered there. Although a dozen or so deep wells penetrate these reservoirs, little public information is available at this time.

Such high temperatures and highly saline brines have not been found in the other thermal anomalies drilled to date. Temperatures from 100 to 200 C and brines containing from 3,000 to 20,000 ppm total dissolved solids are much more characteristic. Similarly, the degree of metamorphism observed is characteristically less than that seen in rocks from the Salton Sea and Cerro Prieto fields (Elders, 1979).

Surface expression of these thermal anomalies is retarded by impermeable caprocks. For example, the Salton Sea geothermal field has an impermeable caprock of lacustrine clays up to 450 m thick (Helgeson, 1968; Randall, 1974). The Dunes hydrothermal system, on the other hand, developed an impermeable caprock by self-sealing. In the upper 300 m of a 612-m deep borehole in the Dunes field, there are seven intervals of intense cementation of sandstone to quartzite, with densities as high as 2.55 g/cm^3 and porosities as low as 3 percent (Elders and Bird, 1974; Bird, 1975).

The hottest geothermal fields (Salton Sea - 365 C, Cerro Prieto - 370 C, and Brawley - 300 C) are all situated in young pull-apart zones. The other geothermal fields such as Heber and East Mesa are associated with the less active extensions of the transform faults. These geothermal fields are under active development as sources of steam for generation of electricity. The most developed is the Cerro Prieto field in Mexico, which already has an installed capacity of 180 MWe and two plants each of 220 MWe under construction. For environmental and technical reasons, development of geothermal power sources has been slower in the Imperial Valley. At this point only pilot scale plants, with net ratings of about 10 MWe, exist at the East Mesa, Brawley and Salton Sea sites. According to published estimates of the U. S. Geological Survey (Muffler, 1979), the geothermal resources available for power generation north of the international border are sufficient to generate 2,000 MWe for a century. This estimate, based upon data available in 1978, must now be regarded as a minimum value. The subsequent discovery of the East Brawley field and recent developments and step-out drilling in the existing fields suggests that the source may be much larger (see discussion in section 1.2.1.1). Because much of these new data are proprietary, however, a precise estimate cannot be made at present.

1.1.3 Ground Water in the Salton Trough

Water wells and wells drilled in the search for oil and geothermal resources in the Salton Trough penetrate a variety of waters that differ in isotopic ratios and salinity. These data are used not only to determine the origin of the water and the salt, but also to determine the degree of interaction of a given groundwater sample with a hydrothermal system.

1.1.3.1 Oxygen and Hydrogen Isotope Investigations

The primary stable isotopic species in water are H_2O^{16}, H_2O^{18}, and HDO^{16} (where D = deuterium). The ratio of these species can be employed for a variety of hydrological investigations. Craig (1963) showed that stable isotope measurements are useful in determining the origin of water in geothermal systems because:

(1) The oxygen and hydrogen isotopic compositions of meteoric precipitation differ from one locality to another due primarily to differences in the temperature of precipitation. Craig

(1961) found a linear correlation between δD and $\delta^{18}O$ for meteoric water samples from all over the earth such that

$$\delta D = 8\delta^{18}O + 10.$$

Samples from colder locations are more negative in δD and $\delta^{18}O$ while precipitation from equatorial zones is closer to Standard Mean Ocean Water (SMOW).

(2) A geothermal system has negligible effect upon the hydrogen isotopic composition of the water flowing through the system because the quantity of hydrogen in rocks is so low. The hydrogen isotopic composition of precipitation which enters a groundwater system and flows through it is generally unchanged. Hydrogen isotopic compositions can thus serve to "tag" waters from different sources.

(3) The oxygen isotopic composition of precipitation which enters a geothermal system can be modified if the system is sufficiently hot (>100 C) due to exchange of oxygen in water with oxygen in the rock. The net effect is to increase the ^{18}O content of the fluid and decrease that of the rock, giving rise to the well known shift of ^{18}O.

Figure 1-2 plots δD versus $\delta^{18}O$ for waters from the Imperial Valley (Coplen et al., 1975) and compares them with the meteoric water line of Craig (1961). Coplen et al. (1975) showed that waters from irrigation wells in the central Imperial Valley plot on a line connecting lower Colorado River water (Lake Mead) to surface water from the Salton Sea, at the lowest point of the closed basin. This regular relationship indicates that the non-geothermal waters of the valley follow a trend of evaporation, becoming heavier in both hydrogen and oxygen as the subsurface flow moves northward.

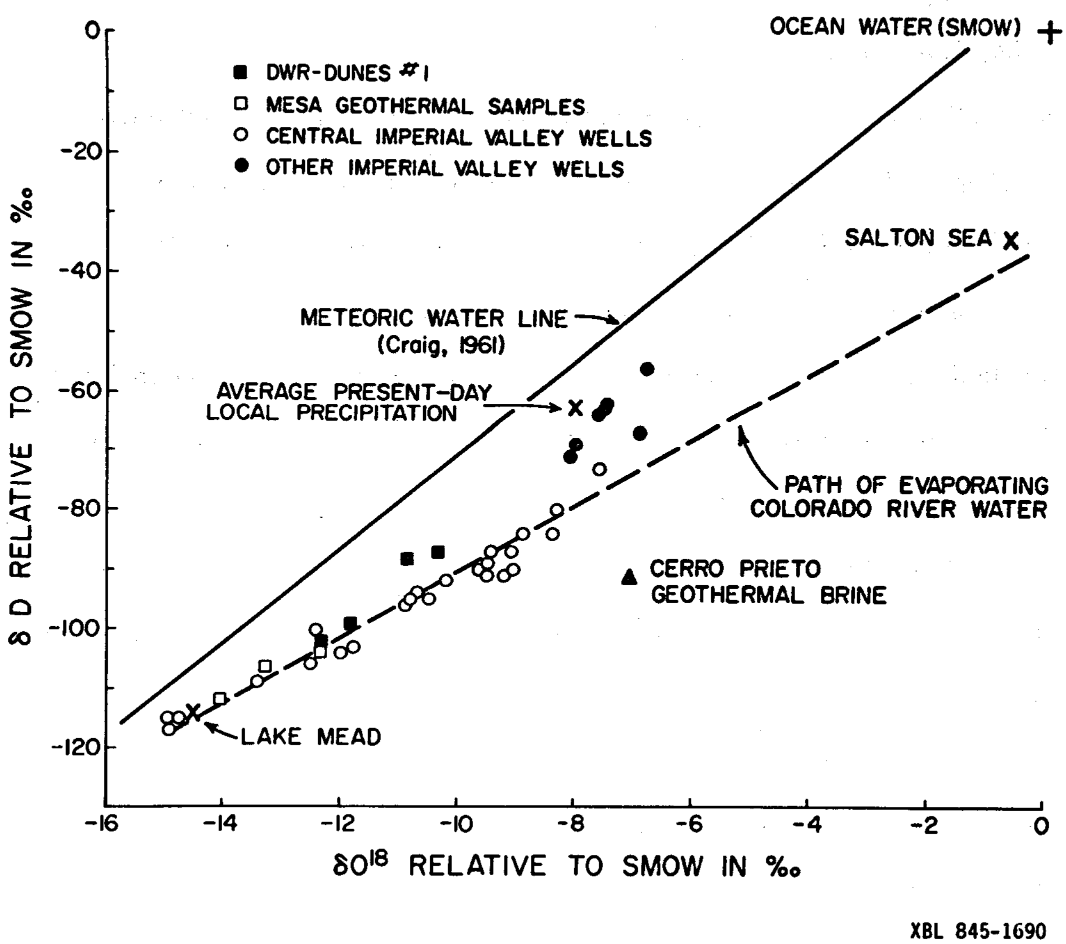

Figure 1-2. δD versus $\delta^{18}O$ of hydrothermal and well water samples from the Imperial Valley area. Source: Coplen et al. (1975).

This isotopic relationship is consistent with the hydrologic studies of Loeltz et al. (1975), which indicate that groundwater recharge into the Imperial Valley occurs almost exclusively by inflow of the Colorado River at Yuma, Arizona. Only near the margins of the Trough in a few shallow aquifers is there significant water derived from local precipitation, as shown by the solid circles in Figure 1-2 (Coplen et al., 1975).

Isotopic ratios of three selected geothermal systems are also plotted in Figure 1-2. A typical high-intensity geothermal sample (Cerro Prieto) shows an isotopic shift of about 3 per mil in oxygen due to water-rock reactions at high temperatures. Samples from a moderate temperature geothermal system (East Mesa, in which temperatures do not exceed 200 C at 2 km) and a low temperature geothermal system (the Dunes, with temperatures of 100 C at 600 m) plot close to the evaporation line. These isotopic data suggest that the waters in these geothermal systems are derived from evolved and evaporated Colorado River water and have not reacted with rocks to exchange oxygen at temperatures greater than 200 C. Because there is little oxygen exchanged in these low to moderate temperature systems, a water/rock ratio for oxygen cannot be determined (Coplen et al., 1975).

1.1.3.2 Brine Types

All deep waters in the Salton trough are primarily NaCl brines. The origin of the salts and waters in a geothermal system may be different; this possibility is discussed by Rex (1972) for the Cerro Prieto geothermal system. Although the isotopic ratios of the water suggest partly evaporated Colorado River water as the source of fluids at Cerro Prieto, the salts in this system appear to be marine. The ratio of chloride to bromide in water has been used to investigate the origin of salt in these geothermal systems (White, 1970;

Rex, 1972). Cl/Br ratios in waters of the ocean and Cerro Prieto geothermal field are 300 and 400, respectively. This suggests that the salt in the Cerro Prieto system is marine in origin. In contrast, White (1968) has suggested that the very saline brine in the SSGF (containing 280,000 ppm TDS) is derived from the solution of evaporites which were formed from Colorado River water (containing 800 ppm TDS). Because the ratio Cl/Br of water from both the SSGF and the DWR Dunes No. 1 (4000 ppm TDS) is 1600, which is identical with that from the Colorado River, it seems likely that the source of the salts in the geothermal fields of the Imperial Valley is Colorado River water (Coplen et al., 1975). However, the situation is probably not so simple. Rex (1972) pointed out that Cl/Br ratios in evaporites are usually highly variable and the Cl/Br ratio of salt from local precipitation is much lower than 1600. Thus it may be only coincidental that the Cl/Br ratio is identical in these hydrologic systems.

More recent studies by Rex (1983) on the origin of the brines in the Imperial Valley point out some of these complexities. Rex (1983) suggested that the geothermal brines are derived from several sources including local precipitation, fossil lake waters from former lakes formed when the flow of the river filled the basin with brackish water, and dissolution of the saline residue from dehydration of these lakes. According to Rex (1983), because rocks contain very little Cl and Br, the Cl/Br ratio is unaffected by geothermal processes and serves as a useful genetic and mixing tracer. On this basis Rex (1983) recognizes six types of subsurface brines in the Salton Trough:

<u>Type 1</u> is a deep metamorphosed brine resulting from chemical equilibration of cold hypersaline NaCl brine with rocks hotter

than 300 C: they are convectively mixed and have Cl/Br 20,000.

Type 2 shows increasing salinity with increasing temperature, with the increasing temperature offsetting salinity-caused density increases, as described by Helgeson (1968): Cl/Br range from 1,200 to 1,300 due to mixing Type 1 brine with Type 3.

Type 3 is a hypersaline brine significantly modified by mixing with fossil lake waters (Type 4). This mixing causes precipitation of metal sulfides, sulfates, oxides, and carbonates in the host rock. The resultant brine has a lower Cl/Br ratio due to the higher Br content of Type 4 water.

Type 4 is water from ancestral Lake Cahuilla.

Type 5 is local precipitation runoff originating from marine air. It is concentrated by evaporation and enriched in sodium and bicarbonate by reaction with rocks at low temperatures.

Type 6 is the unreacted underflow of brackish water entering the valley from the Colorado River drainage.

In addition, Rex (1983) postulates a hypothetical Type 0 brine which is brine formed at 20 C by saturating water by halite. Type 0 would have a density of 1.2, would form within the salinas of the Salton Trough, and could descend along fracture networks into the reservoir. According to Rex (1983) the Heber and East Mesa fields contain mainly Type 4 waters. South Brawley, East Brawley, and Salton Sea geothermal fields contain Type 2 brines. Type 1 brine is apparently found in the I.I.D. #1 well in the SSGF which has the highest chlorinity of any of the wells.

1.2 THE SALTON SEA GEOTHERMAL FIELD

1.2.1 Introduction

The Salton Sea Geothermal Field (SSGF) is one of the best known geothermal fields in the world. Although not as extensively drilled as Cerro Prieto, the SSGF is well-known because it was one of the first fields to be drilled in the U.S.A. for a source of electric power, because of its great size, and because of its high temperatures. The SSGF is also well known for the problems that its highly saline brines pose for power production, and for the opportunities and challenges presented by the high content of metals and brines contain. The following has been taken from a review of SSGF by Elders and Cohen (1983).

1.2.1.1 Resource Estimates

According to Muffler (1979), the reservoir volume of approximately 116 km^3 explored by drilling to that time, and having a mean temperature of 330 C, contained about 1×10^{20} Joules. Assuming a porosity of 20 percent and assigning a reasonable recovery factor and thermal efficiency factor, the estimated electrical energy potential for the SSGF is 3400 MWe for 30 years (Muffler, 1979). On the other hand, Meidav and Howard (1979) point out that Lee and Cohen's (1979) shallow heat flow data indicate that the area exhibiting conductive heat flow greater than 200 milliwatts/m^2 (4.8×10^{-6} cal cm^{-2} s^{-1}) may cover more than 560 km^2. Meidav and Howard (1979) therefore suggested that a reservoir 2 km thick underlying this area, with a mean temperature of 265 C, should contain 5.86×10^{20} Joules. Thus their estimate of the recoverable energy is 19,900 MWe for 30 years, six times that made by the USGS. Based upon the area of the magnetic and gravity anomaly associated with the field, Younker and Kasameyer (1978) estimated the recoverable heat to lie between 870 and 5800 MWe for 30 years. The true size of the resource can only be determined by extensive well-testing and reservoir engineering analyses. Unfortunately the data from many studies are proprietary and hence these analyses have not been done on a field-wide basis.

In spite of the evident large size of the resource, the first power plant within the field, a 16 MWe (gross) pilot-scale plant, has been operated only since 1982 by the Southern California Edison Company (location in Figure 1-3). The slow rate of commercial development is due to the environmental and technical problems of handling brines containing 28 wt percent TDS. These problems include both corrosion and scaling. Since their first discovery, however, the brines have also presented the challenge of using them as a source of recoverable metals (White et al., 1963).

Recently Maimoni (1982) estimated the potential for minerals recovery from a 1000 MWe combined geothermal power and minerals recovery plant in the SSGF. This author pointed out that a 1000 MWe plant, selling electric power at 6 cents/kWh, could earn $394 million/year in 1982 U.S. dollars. This plant would require a brine flow rate of 45 million kg/h. Assuming 90 percent of the mineral values could be recovered, the market value of the minerals produced would be about $500 to $1,500 million/year. The wide range reflects the uncertainties about the content of precious metals. The estimate excludes lithium since the potential production from the SSGF could be an order of magnitude greater than the 1980 total world sales. The plant could supply 14-31 percent of the U.S. demand for manganese, a strategic material. This brine field may also potentially constitute the largest reserve of platinum in the U.S.A. (Maimoni, 1982). In spite of the large value of the

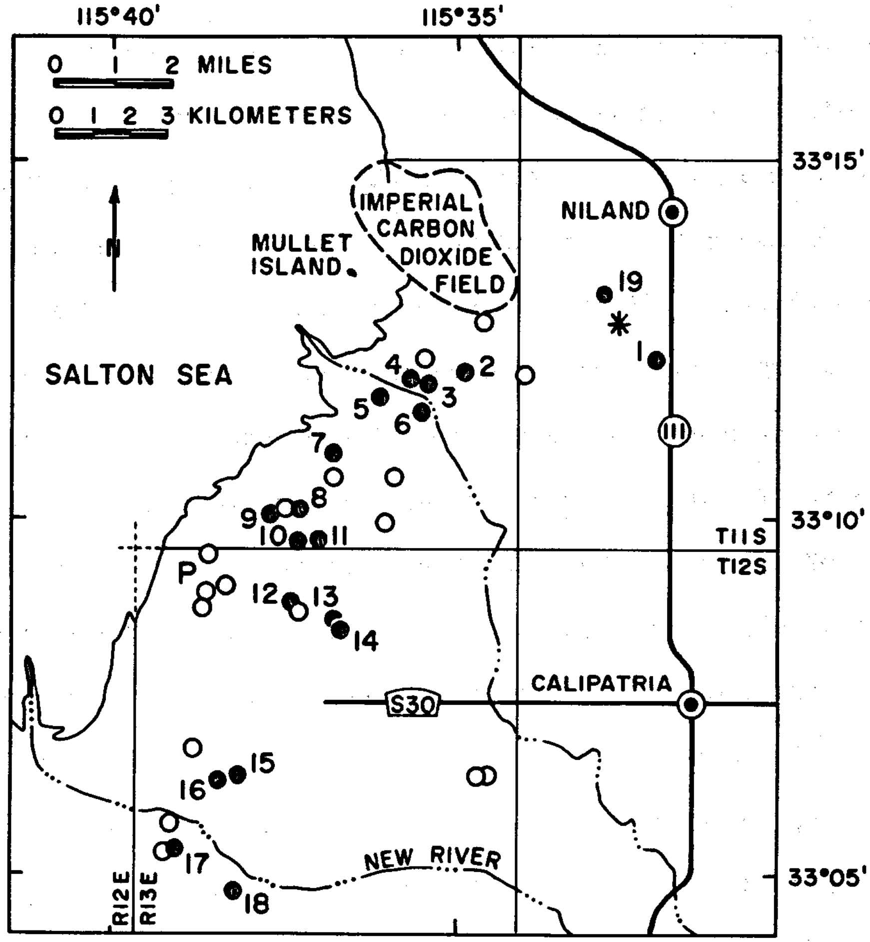

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Figure 1-3. Location of Existing and Proposed Geothermal Wells in the Salton Sea and Westmoreland Geothermal Areas (Source - Muramoto, 1982). P - location of SCE power plant; ● - geothermal wells for which samples and/or logs exist at UCR; o - other geothermal wells; * - proposed well Fee No. 5 (Republic Geothermal, Inc.).

Number on Map	Well Name	Number on Map	Well Name
1	Britz No. 3	10	Magmamax 1
2	River Ranch No. 1	11	Woolsey No. 14
3	Sportsman No. 1	12	Sinclair No. 4
4	I.I.D. No. 1	13	Sinclair No. 1
5	I.I.D. No. 2	14	Sinclair No. 3
6	State of California No. 1	15	Landers No. 1
		16	Landers No. 2s
7	Elmore No. 1	17	Dearborn Farms
8	Magmamax No. 3	18	Kalin Farms
9	Magmamax No. 2	19	Fee No. 1

metals in solution which would pass through such a plant, however, it is by no means clear that the techniques available to recover them would be economic at the present.

1.2.1.2 History of Development

Geothermal fields in the Salton Trough are typically cryptic, i.e., they are not associated with surface manifestations of geothermal activity such as hot springs, geysers, mud pots, or fumaroles except for the Cerro Prieto and Salton Sea geothermal fields. Mullet Island (Figure 1-3) is one of the five small rhyolite domes associated with SSGF (Robinson et al., 1976). Live steam fumaroles, mud volcanoes and boiling mud pots were noted there by local inhabitants before the area was inundated by the rising lake, the modern Salton Sea, in 1906 (Lande, 1979). A small remnant area of mud pots is still visible about 4 km southeast of Mullet Island. The first attempt to exploit the geothermal resources of the SSGF was by the Pioneer Development Company, which drilled three wells near Mulett Island in 1927 and 1928. The deepest reached 450 m and all three produced steam, boiling water and carbon dioxide, but not in sufficient quantity for commercial development (Lande, 1979).

The occurrence of CO_2 led to further exploration drilling. In 1932 the Imperial carbon dioxide field, which produced commercially from 1933 to 1954, was discovered northeast of Mullet Island (Figure 1-3). Carbon dioxide, 98 percent pure, was produced from shallow sands 60 to 220 m below the surface and was used to produce dry ice for refrigeration. Abandonment of the field in 1954 came about by the development of modern refrigerated transport and was hastened by the rising waters of the lake, which inundated many of the wells (Lande, 1979).

In 1957 the Sinclair No. 1 well, an oil and gas prospect, was drilled to a depth of 1400 m and produced hot water and steam. This well scaled shut near the surface shortly afterwards. In 1961 the first well to be drilled expressly for steam, the Sportsman No. 1, was completed to 1500 m, about 6 km northeast of Sinclair No. 1, and was a good steam producer. In the next three years ten new geothermal wells were drilled in the vicinity, eight of which were good producers. These wells showed brine concentrations of up to 280,000 ppm TDS. Recognizing their potential, Morton Salt Company and Union Oil Company erected small pilot plants to experiment with brine handling. After several years of effort these facilities were abandoned as uneconomical.

After a period of inactivity, five new exploration wells were drilled in the SSGF during 1972 in a renewed search for alternate energy. A pilot brine-handling facility was jointly operated by the Department of Energy, San Diego Gas and Electric Company, and Magma Power Company from about 1976 to 1979. Since that time more than a dozen new wells have been drilled, so that today more than 32 deep wells exist in the field (Figure 1-3). Apart from the 16 MWe power plant operated by Southern California Edison Company, plants of 50 MWe are being planned both by Magma Power Company and Parsons Engineering, Inc. for the near future.

1.2.1.3 Previous Opportunities for Studies of the SSGF

Although publication of earth science-related work on the SSGF has been hindered by the limitations of dealing with proprietary data, there has been a significant number of published studies on this field. Most information was released in 1961-1968 during the first rush of enthusiasm for development when the novelty of the discoveries being made, coupled with the disappointing commercial results, created a climate where release of proprietary information was possible. Another fairly open situation for release of data occurred during the period 1974-1979 in connection with the test facilities which operated using brine from wells drilled by the Magma Power Company. Since that time, the major operators in the field have for corporate reasons kept proprietary the information on the newer wells. The latter now exceed the number drilled prior to 1979 (Figure 1-3).

1.2.1.4 Some Previous Publications on the SSGF

Five years after the initial report of discovery of this hot hypersaline geothermal system (White et al., 1963), a pioneering report on many aspects of its chemistry and thermodynamic properties appeared (Helgeson, 1968). This work was followed shortly thereafter by the first discussion of the active greenschist facies metamorphism going on within this system (Muffler and White, 1968). In 1974 the first attempt at understanding the subsurface geology using wireline logs was completed (Randall, 1974) and, about the same time, a useful compilation of water analyses and other data was published (Palmer, 1975). The associated volcanic rocks were first described by Robinson et al. in 1976 and a more detailed study of metamorphic reactions in the field appeared in 1980 (McDowell and Elders, 1980). Finally, in 1982, a comprehensive review of the geological and geophysical characteristics of the SSGF, together with a simplified thermal model, appeared (Younker et al., 1982).

1.2.2 Geophysical Anomalies Associated with the SSGF

The geophysical characteristics of the SSGF are well summarized in Younker et al. (1982). As well as being a locus of high heat flow and high temperatures, the field is associated with positive gravity, magnetic and seismic velocity anomalies, low electrical resistivity, and high microseismicity.

The gravity maxima have been attributed to either an increase in density of the sediments resulting from hydrothermal alteration, or the intrusion of dikes and sills into the sedimentary section, or both (Elders et al., 1972). By far the largest of these local maxima, centered on the Red Hill volcano in the SSGF, corresponds to a residual Bouger anomaly of +23 milligals (Biehler, 1971) that is much too large to be due only to densification of sediments or presence of sporadic dikes or sills. Instead, the emplacement of a larger volume of mafic igneous rock seems required. The above hypothesis is supported by the magnetic signature of the SSGF. Magnetic surveys by Kelly and Soske (1936) and Griscom and Muffler (1971) reveal the presence of rocks with high magnetic susceptibility and remanent magnetization at fairly shallow depth.

The association of a gravity anomaly with a seismic travel-time anomaly in the SSGF has been reported by Savino et al. (1977). Observations of a seismic velocity-depth anomaly reported by Frith (1978) may be due to reduction of porosity as a result of hydrothermal alteration and intrusion of basaltic material. Meidav et al. (1976) have used electric techniques and found resistivities of less than 0.5 ohm-meters to depths of several kilometers. The low resistivity coincides with high temperature and high salinity. This concept has been confirmed by telluric soundings made by Humphreys (1978).

1.2.3 Temperatures and Heat Flow within the SSGF

The most comprehensive published compilation of temperature information from the SSGF is in Younker et al. (1982). Temperatures typically exceed 320 C at 2 km depth, with the highest reported to date being 365 C at 3100 m in the Elmore No. 1 borehole. Figure 1-4 shows the isotherms at 914 m (3000 ft)

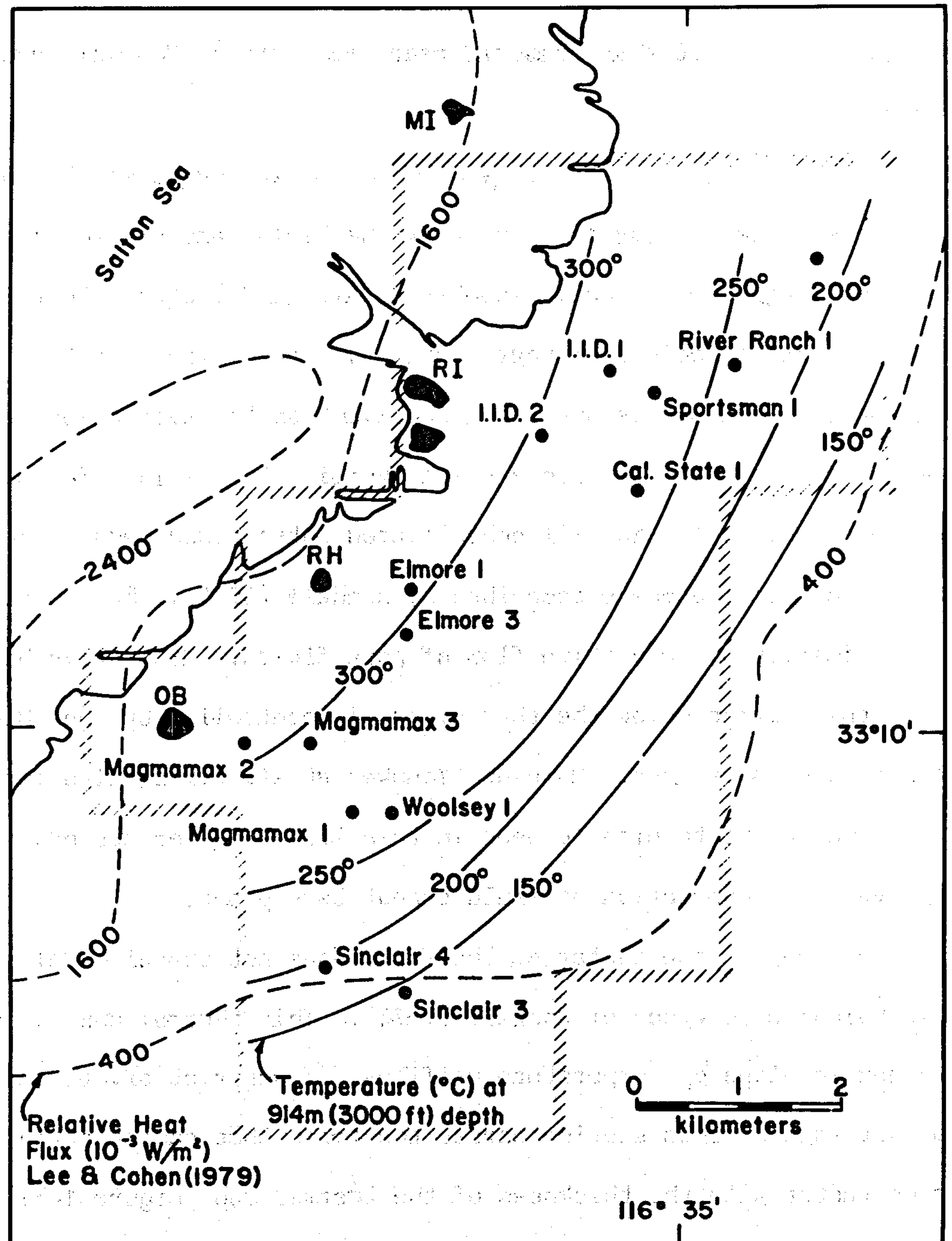

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Figure 1-4. Location of boreholes and isotherms at 914 m (3000 ft) depth in the Salt Sea Geothermal Field

Solid lines = temperature (C), modified after Palmer (1975) and Randall (1974). Dashed lines = relative heat flux in 10^{-3} watts/m^2 from Lee and Cohen (1979). Rhyolite extrusive: OB = Obsidian Butte; RH = Rock Hill; RI = Red Island; MI = Mullet Island. Hachured line //// = outline of the Salton Sea KGRA as originally defined. The boundaries have since been extended. (Source - McDowell and Elders, 1980).

depth and contours of heat flux measured near the surface (McDowell and Elders, 1980).

Typically, gradients are very steep (0.38 C/m) in the upper 600 to 700 m of nine of these 13 wells near the center of the field, and are an order of magnitude lower at greater depths. Younker et al. (1982) attribute this change to different mechanisms of heat transfer. They infer that the steep near-surface gradient is due to conductive heat transfer associated with an impermeable clay-rich caprock which overlies the field. Below this is a zone, in a moderately- to well-consolidated interbedded sandstone-siltstone-mudstone deltaic sequence described by Randall (1974), where heat transfer is primarily by convective flow of pore fluids. Convective heat transport in the section below the thermal cap is controlled by the thickness of the sandstone beds present. However, Younker et al. (1982) also infer that flow is impeded by thin shale beds in this lower aquifer system. Thus large-scale vertical convection of fluid cannot take place.

The thermal cap in the center of the field does not exactly conform with the lithological caprock of Randall (1974). This thermal cap is inferred from the break in slope of temperature profiles. Younker et al. (1982) plotted a north-south cross section across the field that compared the reservoir character with the thickness of the thermal cap (Figure 1-5). The base of the thermal cap is often within a zone containing greater than 20 percent sand (Towse and Palmer, 1975), and the first appearance of high reservoir quality is also at the base of the thermal caprock. These observations support the authors' interpretation that the dominant controls on heat transport are thick sandstone beds and intervening shales. Fracture permeability of the shales, however, may be locally significant (Younker et al., 1982).

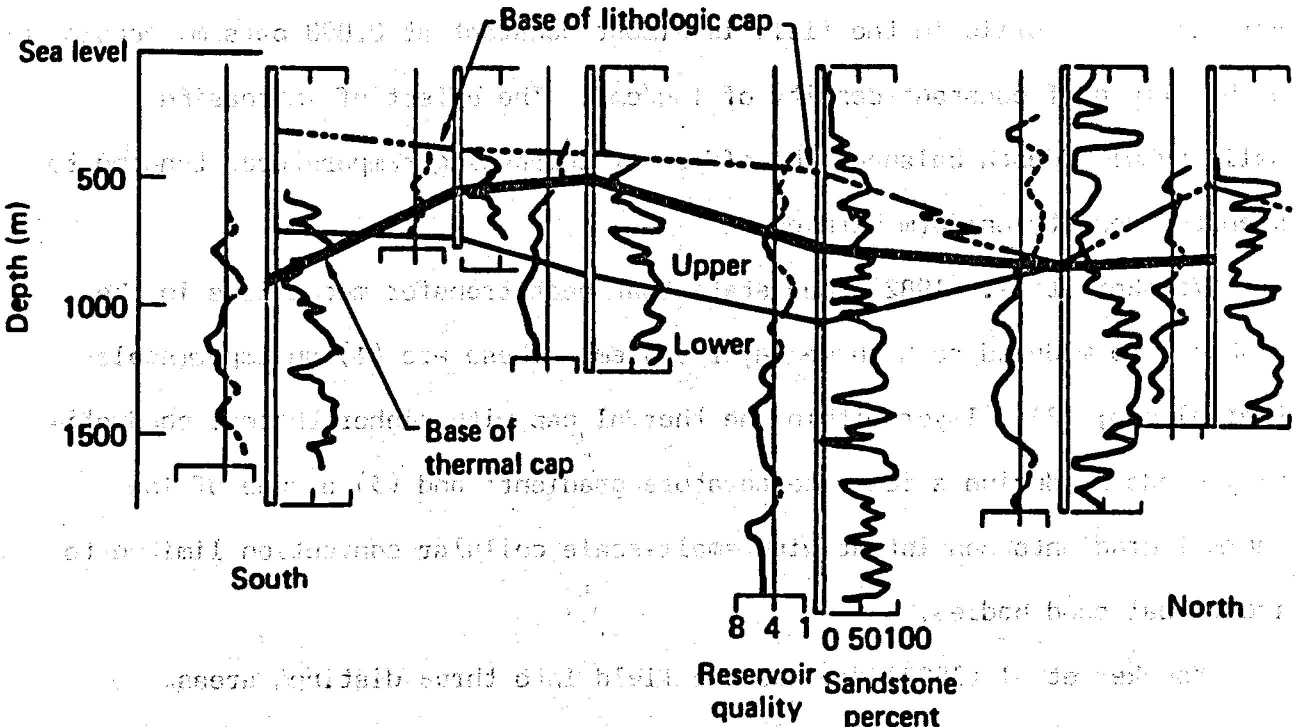

Figure 1-5. North-south section across the Salton Sea Geothermal Field showing the thermal and lithologic caps.

Sandstone percentage, a subjective measure of reservoir quality (Towse, 1975) and the depth to the base of the thermal cap are shown for six wells. From south to north, the wells are Sinclair #4, Woolsey #1, Magmamax #3, Elmore #1, I.I.D. #2, and Sportsman #1 (Source - Younker et al., 1982).

Morse and Thorsen (1978), on the basis of reservoir engineering tests, calculate that the reservoir has horizontal permeabilities of 100 to 500 md while vertical permeabilities across shale layers are only 0.1 to 1.0 md. Another factor precluding large scale vertical convection is the density profile of the brines. Helgeson (1968) showed that the hydrostatic pressure-versus-depth profile in the field is almost constant at 0.098 bars/m, consistent with a fluid of constant density of 1 g/cm^3. The effect of increasing salinity with depth balances the effect of increasing temperature, tending to keep the density uniform with depth.

Younker et al. (1982) thus state that heat transfer mechanisms in the SSGF can be modeled as a three layer system. These are (1) an impermeable thermal cap; (2) a layer within the thermal cap with higher thermal conductivity sands producing a lower temperature gradient; and (3) a zone of low thermal gradients consistent with small-scale cellular convection limited to individual sand bodies.

Younker et al (1982) divided the field into three distinct areas. First, there is a central zone with nearly constant vertical conductive heat flow having a thermal cap with gradients of 0.4 C/m and overlying a nearly isothermal zone extending to 2000 m depth. Next is an intermediate region with a low near-surface temperature gradient that increases at greater depths. Finally, to the southeast is an outer zone with nearly uniform and lower shallow gradient of 0.1 C/m, similar to the normal regional values. This overall pattern is consistent with a large-scale horizontal flow in layer three which transfers heat from the area of the volcanic domes southeast towards the margins of the field.

1.2.4 Brine Chemistry in the SSGF

The brines in the SSGF are concentrated sodium, calcium, potassium chloride solutions containing some of the highest concentrations of dissolved metals known in nature. These brines are comparable in their heavy metal concentrations to the unusually high salinity brines which have been produced from geothermal wells in the Cheleken anticline, on the east shore of the Caspian Sea (Lebedev, 1973), and from the enclosed deeps in the Red Sea (Degens and Ross, 1969). White (1981) calculated that the estimated volume of 116 km^3 of the SSGF (noted in section 1.2.1.1: i.e., depth of 3 km, mean reservoir temperature 330 C, and assumed porosity 10 percent) contained the following valuable elements in metric tonnes:

Zn	5×10^6;	Pb	9×10^5;
As	1.2×10^5;	Cu	6×10^4;
Cd	2×10^4;	Ag	1×10^4;
K	1.7×10^8;	Li	2.2×10^6;
B	4×10^6;	Cs	1.5×10^5;
Tl	1.4×10^4;	Mn	1.6×10^6.

If, as seems apparent from the work of Humphreys (1978), these high salinity brines extend from the SSGF to the Brawley Geothermal Field, then the volume of accessible concentrated brines could be an order of magnitude greater than the estimate made by White.

The chemistry of SSGF brines was first reported by White et al. (1963). Later Craig (1966) compared their chemistry and isotopic ratios with brines from the Red Sea. Detailed analyses of brines from the early wells were then published by Helgeson (1968), Skinner et al. (1967), and White (1968). Later involvement of staff of Lawrence Livermore National Laboratory in studies of wells supplying the San Diego Gas and Electric Geothermal Test Loop

Experiment Facility, from 1975-1978, led to a compilation of data on these wells (Palmer, 1975) and studies of various aspects of the brine chemistry (Harrar et al., 1979; Austin et al., 1977; Maimoni, 1982).

Table 1-1 summarizes the chemical compositions of wells drilled before 1975 in the central portion of the SSGF (well locations appear in Figure 1-3). Geothermal brines are notoriously difficult to sample. At the well-head they consist of a multiphase mixture of condensible and uncondensible gas, liquid, and suspended solids. Normally the greatest problem is to evaluate the steam loss due to boiling before a sample is taken. Thus there may be sampling errors as well as possible analytical errors in reported values. Additional errors are introduced due to reactions within the brines on quenching to room temperature, e.g., the precipitation of barium sulfate before sample analysis. A further problem is that the well-head compositions vary with changes in flow rates, possibly due to tapping different aquifers or fracture systems at different well-head pressures.

Salinity varies both vertically in a given well and horizontally from well to well. For example, an analysis reported from Fee No. 1 gave a total concentration of 250,000 ppm TDS, whereas two samples from Britz No. 3, the well closest to Fee No. 1, are reported as 116,000 and 133,772 ppm TDS from zones at roughly the same depths. Presumably these differences came from mixing different fluids tapped from different aquifers. Certainly wells in the Westmoreland part of the field (Figure 1-3) have penetrated a much lower salinity system with 14,600 to 72,000 ppm TDS at 950-1800 m depth.

Vertical gradients in salinity are somewhat more difficult to quantify, since geothermal wells are normally completed with an open interval which may be a hundred meters or more thick. Thus brine can flow into the well over a large interval, even though brines in other parts of the section are excluded

Table 1-1. Chemical Compositions of Salton Sea Brines

	I.I.D. No. 1 Skinner et al. (1967)*	I.I.D. No. 1 White (1968)*	I.I.D. No. 2 Helgeson (1968)*	State of Calif. No. 1 Helgeson (1968)*	Woolsey No. 1 Palmer (1975) (maximum ppm values from Magma Power Co.)+	Magmamax No. 1 Palmer (1975)+
Zn	790	540	500	500	---	---
Pb	84	102	80	80	---	---
Cu	8	8	3	2	---	---
Ag	0.8	1.4	2	<1	---	---
Fe	2,090	2,290	2,000	1,200	244	93
Mn	1,560	1,400	1,370	950	488	200
Na	50,400	50,400	53,000	47,800	49,729	52,500
Ca	28,000	28,000	27,800	21,100	12,658	25,000
K	17,500	17,500	16,500	14,000	6,510	5,000
Li	215	215	210	180	90	---
Cl	155,000	155,000	155,000	127,000	83,183	---
SO_4	5	5.4	30 (Total S)	---	---	---
Sulfide S	16	16		30	---	---
Silica	400	400	400	---	181	500
pH	5.2	5.2	4.64	---	6.25	6.65
TDS	258,360	250,000	258,769	219,500	151,237	>100,000
S.G.	---	---	---	---	1.106	1.022
BHT	316 C	340 C	332 C	305 C	238 C	265 C

All compositions are given in ppm unless otherwise noted. Not all analyzed constituents are listed.

* - Known to be corrected for steam loss
+ - Not know if corrected for steam loss
TDS - Total Dissolved Solids in ppm by wt
S.G. - Specific Gravity at 20 to 25 C
BHT - Bottom Hole Temperature
--- - Not reported

	Magmamax No. 1 Needham et al. (1980) (Average of Jan. 1977 tests)	Woolsey No. 1 Needham et al. (1980) (Average chemical analyses Feb. 1977)	Sportsman No. 1 Palmer (1975)+	Sinclair No. 4 Palmer (1975)+
Zn	290**	---	---	600
Pb	44	---	---	60
Cu	0.5	---	---	3
Ag	0.8	---	---	1
Fe	280	235	4,200	1,300
Mn	635	---	---	1,700
Na	38,300	40,000	70,000	78,000
Ca	21,100	16,700	34,470	37,735
K	10,400	9,100	24,000	20,690
Li	150 to 200**	140	150	400
Cl	128,700	99,000	201,757	210,700
SO_4	---	---	34	75
Sulfide S	---	---	---	---
Silica	239	---	5	625
pH	5.5	5.44	4.82 to 6.10	5.0
TDS	>200,000	>150,000	334,987	387,500
S.G.	---	---	1.207	---
BHT	---	200 C	310 C	260 C

** Concentrations from samplings in 1976 by the well casing. A crude estimate of vertical changes in salinity may be made by examining adjacent wells which are completed at different depths. Better still are drill stem tests made during drilling, but these are rarely done and the data are often held proprietary. For the well Sinclair No. 4, Helgeson (1968) estimated the change of salinity with depth by calculating a unit isochore for a simulated brine, as temperature and salinity both rise together. This concept was verified in this well by determining the depression of freezing points of fluid inclusions from various minerals at different depths (Freckman, 1978). These last data indicate approximately 5-10 percent salinity at 220-240 C, whereas there is 15-25 percent salinity at 270-300 C.

1.2.5 Subsurface Geology of the SSGF

The SSGF lies beneath irrigated fields, the ponds and marshes of a bird sanctuary, and the waters of the Salton Sea. The only rocks which crop out are the five small rhyolite domes referred to above (Figure 1-4), and the recent deposits of the former Lake Cahuilla, ancestral to, but larger than, the present Salton Sea.

In spite of the large number of existing deep boreholes, the subsurface sedimentological and paleontological characeristics of the SSGF have never been fully synthesized. Studies of cuttings and cores have hitherto emphasized water/rock reactions rather than sedimentology. Some parastratigraphic and structural studies have been done, however, using wireline logs.

1.2.5.1 Parastratigraphy

The first and most comprehensive parastratigraphic study, done by Randall (1974), was based upon downhole wireline logs, including temperature logs, from 16 wells chiefly in the west-central portion of the field. This study was augmented by that of Tewhey (1977) who, in addition, studied cuttings and cores from the Magmamax No. 2, Magmamax No. 3 and Woolsey No. 1 wells. These data revealed a lithologic sequence of shales and sandstones consisting of (1) a caprock; (2) an upper reservoir of slightly altered rocks; and (3) a lower reservoir of highly altered rocks (Figures 1-5 and 1-6). According to Randall (1974) the caprock is a sedimentary unit primarily composed of lacustrine clays and silts. In the vicinity of the Magmamax wells, the caprock is 340 to 370 m thick and is composed of two distinct layers. The upper 200 m consists of unconsolidated clay and silt which, because of its uncemented nature, is poorly represented in drill cuttings. The lower layer consists of consolidated silts, and sands, with a carbonate cement, intercalated with consolidated silts with anhydrite cement. The anhydrite is presumed to be evaporite layers. These rocks apparently record sequences of inundation and desiccation of freshwater lakes which proceded the modern Salton Sea.

Using combined spontaneous-potential and resistivity logs, Randall (1974) mapped the thickness of the sedimentary caprock (Figure 1-7). Over a distance of six kilometers the caprock varies from zero thickness in the south to 430 m thick in Elmore No. 1. Randall's map (Figure 1-7) shows the caprock as a wedge thickening to the northwest and bounded to the west by a fault detected by the dipmeter log of Magmamax No. 2. The base of this wedge shows considerable relief in the east-west direction. Lack of depth correlation between adjacent wells and led Randall to infer several growth faults which offset the caprock (Figure 1-7).

The caprock lies in apparently unconformable relationship on the underlying upper reservoir sequence. Younker et al. (1982), p. 225) assert that the sharp transition between reservoir rocks and the overlying caprock represents the boundary between lacustrine sediments above and underlying

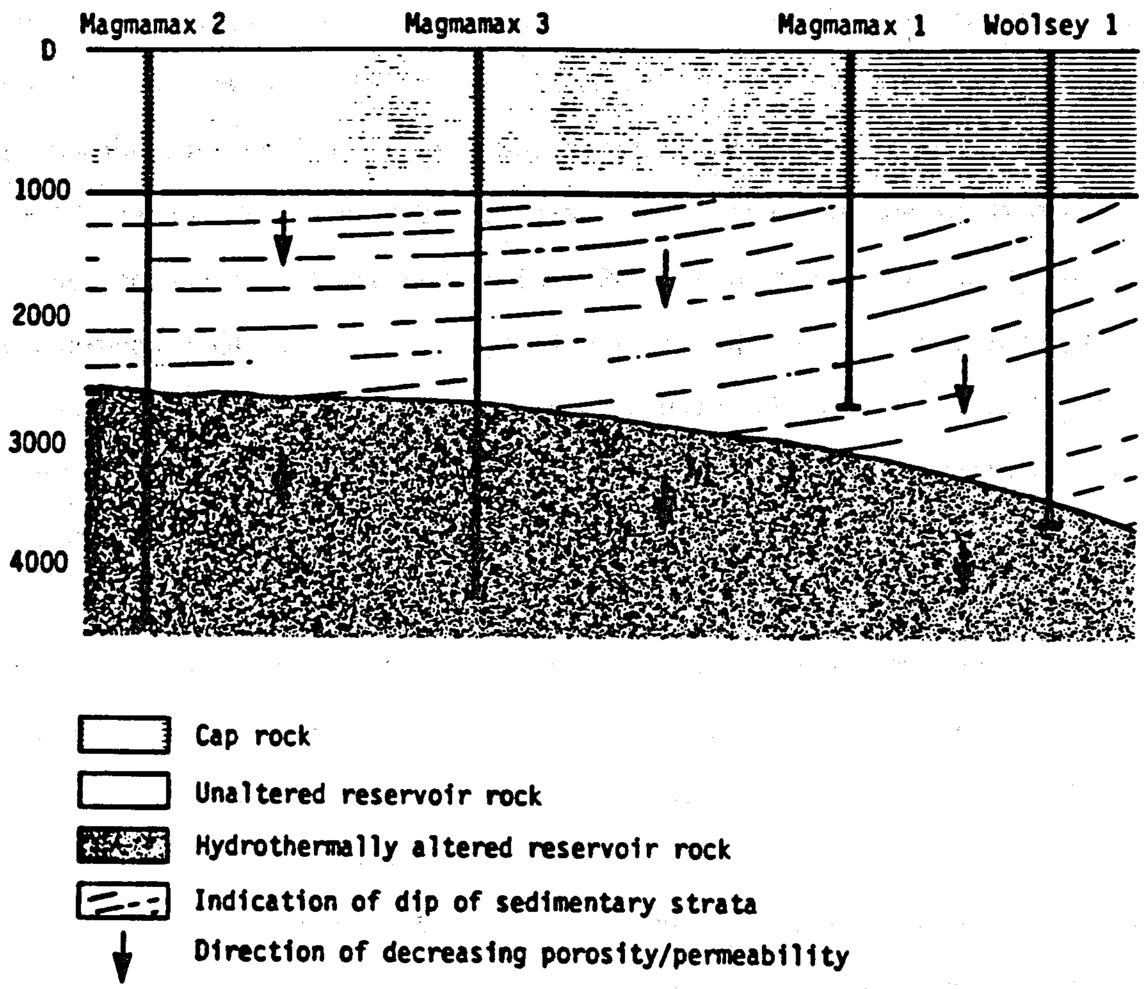

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Figure 1-6. East-west cross section through the Magmamax and Woolsey Wells in the Salton Sea Geothermal Field.

The three rock types, i.e., cap rock, slightly altered reservoir rock, and hydrothermally altered reservoir rock, are classifications based on petrographic analysis. The orientation of strata in the reservoir rock is shown by dashed lines. For well locations see Figure 1-3 (Source - Tewhey, 1977, Figure 23).

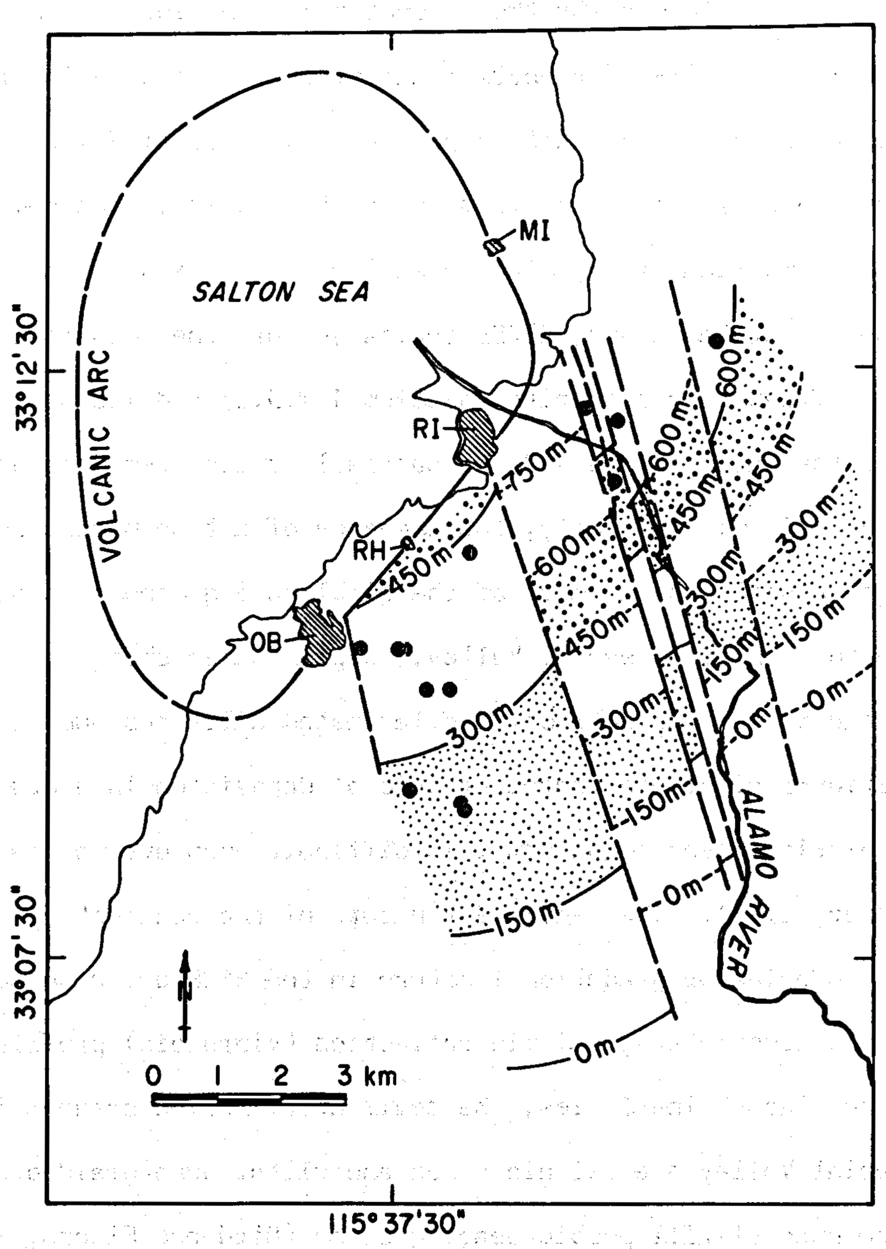

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Figure 1-7. Depth to the base of the sedimentary caprock. The "volcanic arc" of Randall connects a series of small amplitude magnetic anomalies through the five rhyolite domes (modified from Randall, 1974, Figure 5).

"marine sediments", which were deposited before the Salton Trough was isolated from the southern portion of the basin in "mid-Pleistocene" times. However, they do not present evidence for these rocks being "marine" in character.

Although Woodward (1974) reports intermittent shallow marine rocks of mid-Pleistocene age in the western part of the Imperial Valley, there are no published paleontological data from any of the wells in the central portions of the Imperial Valley, including the SSGF (see section 1.1.1). Similarly, as was stated above, Cl/Br ratios support the idea that the origin of the salt is freshwater evaporite (section 1.1.3.2) and isotopic studies indicate that the water is evolved and partially evaporated Colorado River water (section 1.1.3.1). Finally, the presence of a true marine sedimentary facies is not supported by studies of the wireline logs and cuttings here or elsewhere in the central Imperial Valley. Rapid facies changes, involving lenticular sand bodies and intercalated laminated silts and mud rocks with steep depositional dips, are characteristic of deposition in a prograding delta. Correlation, even at outcrop, is difficult even over a few hundred meters (Wagoner, 1977). The lenticular nature of the sedimentary units and their steeply dipping progradational nature in the SSGF are also most apparent in unpublished, proprietary, seismic reflection (Vibroseis) profiles.

Apart from lacustrine facies, the sedimentary facies present in the central Imperial Valley are deltaic sands and silts, dune-braided stream deposits, and channel-fill pebble-bearing sands (Bird and Elders, 1975), none of which have a true marine aspect. The upper reservoir in the SSGF consists of terrigenous deltaic sands, silts and muds, with occasional lacustrine and stream deposits. The sands are indurated quartz feldspar arenites and lithic wackes containing minor detrital mica and chlorite, with varying degrees of calcite cement and intergranular porosity of 10 to 30 percent. The amount of cite cementation is greatest near the top of the section, beneath the clay caprock. With increasing depth and temperature, dissolution of carbonates can lead to appreciable secondary porosity. The argillaceous rocks are indurated mudstones and fine-grained siltstones consisting of clay-sized quartz, feldspar, and calcite together with kaolinite, montmorillonite and detrital illite as the chief clay minerals (Muffler and Doe, 1968). Although sporadic thin lignite beds are present, caution is necessay in estimating their thickness, as most lignite seen in borehole cuttings is a drilling mud additive.

In the west-central portion of the SSGF the thickness of the upper reservoir zone is 500 to 600 m; however, in the eastern part of the field near Niland, the upper reservoir zone is much thicker and the sedimentary section is much more argillaceous. With increasing temperature, there is a fairly rapid transition into the lower reservoir which consists of indurated hydrothermally altered reservoir rocks. Younker et al. (1982) define the top of the upper reservoir as being the first appearance of authigenic epidote at 280 C. However other workers have observed epidote appearance at 225 C (McDowell and Elders, 1979, 1980). Randall (1974) defined the top of the lower reservoir as being the top of a metamorphic zone where shales and carbonates react to form chlorite by decarbonation reactions. The physical changes accompanying these reactions cause marked loss of porosity in the shales and cause them to acquire electrical log characteristics similar to carbonate rocks (low spontaneous potential and high resistivity). Invariably, sandstones and siltstones are affected more by recrystallization than are less permeable shales. The changes induced by reactions of the rocks with hot brines eventually lead to destruction of porosity and reduction in permeability (Figure 1-8) with increasing temperature.

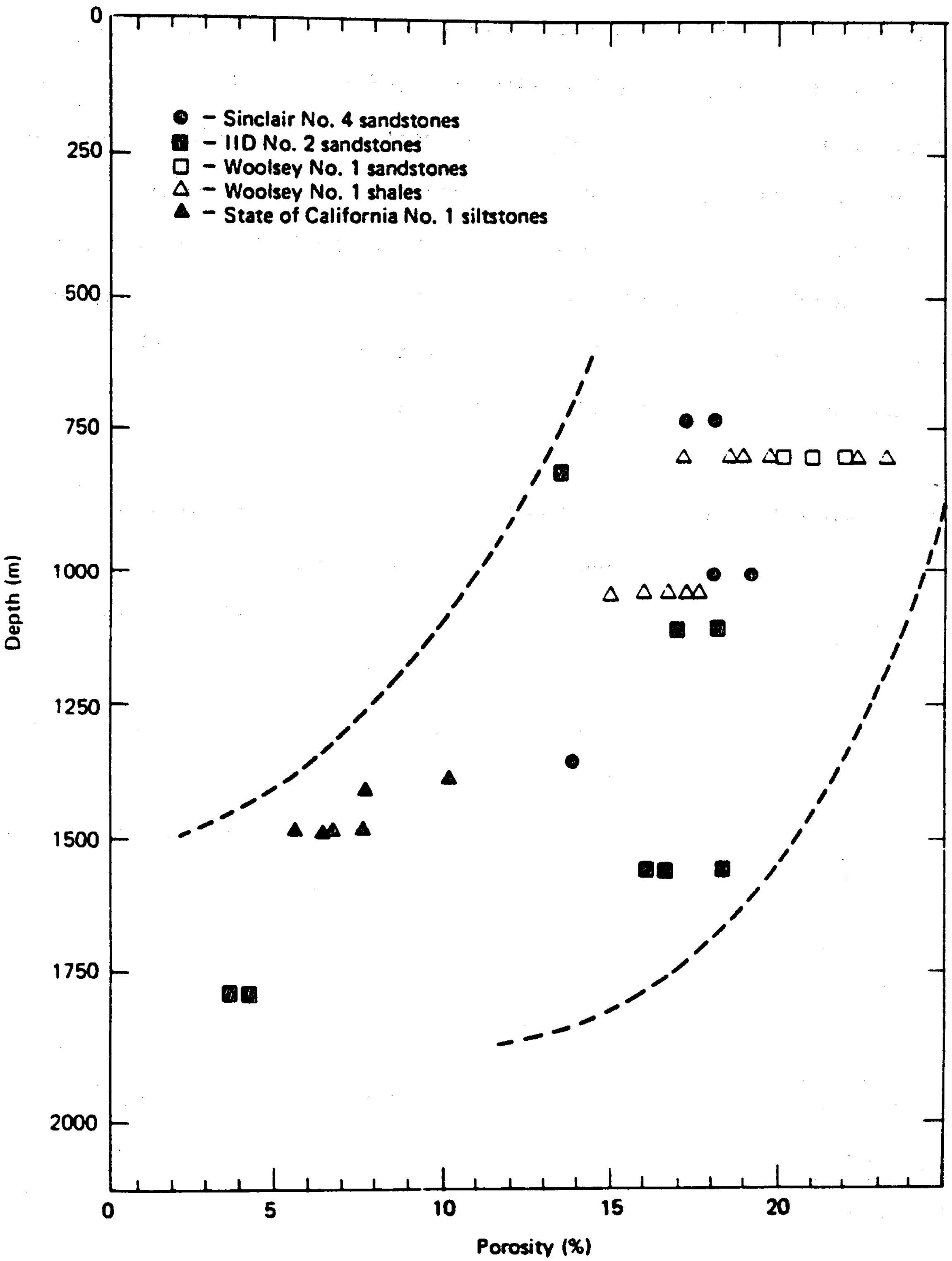

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Figure 1-8. Measured porosity versus depth for cores from five geothermal wells in the Salton Sea Geothermal Field.

(Source - Younker et al., 1982, Figure 4).

1.2.5.2 Subsurface Structure

In the west-central portion of the field, in the area studied by Randall (1974) and Tewhey (1977), the strata dip west at 10°. Although correlation is difficult, Randall (1974) attempted correlations between 16 wells by defining parastratigraphic units using percentage volume of sand bodies per 160 m (500 ft) intervals (Figure 1-9). Randall also was able to correlate certain distinctive marker beds between some adjacent wells. Using spontaneous potential logs, he was able to correlate sand-shale boundaries and thicknesses of distinctive units. Such cross sections define a broad syncline with an east-west axis plunging gently west. A general tendency for thickening of individual sedimentary units from north to south was also found.

1.2.5.3 Influence of Structure on Heat Transfer

One of the important outcomes of these parastratigraphic and structural studies was the finding that the isotherms are not controlled to any apparent extent by local sedimentary stratigraphic and structural relationships (Randall, 1974). Isothermal surfaces are seen to transect sedimentary bedding, ignoring the strike and dip of the strata. Similarly the temperature cross sections seem unaffected by the locations of postulated faults. Randall (1974) therefore concluded that distance from a postulated magmatic heat source is almost the sole determining factor for the shape and size of the thermal anomaly.

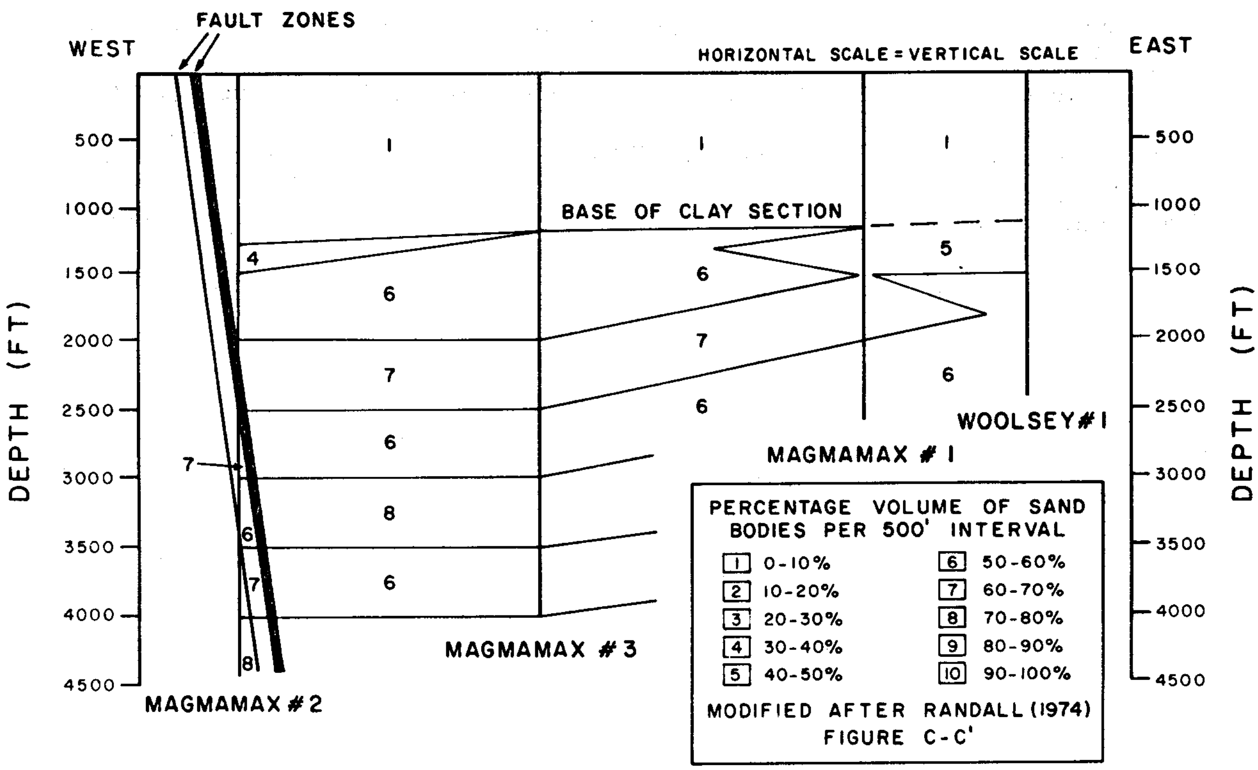

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Figure 1-9. Parastratigraphy of the Buttes Area. For well locations see Figure 1-3 (Source - Kendall, 1976, after Randall, 1974).

1.3 THE PROPOSED SALTON SEA SCIENTIFIC DRILLING PROJECT

1.3.1 Continental Scientific Drilling

The report entitled Continental Scientific Driling Program, published in 1979 by the U. S. Geodynamics Committee of the National Research Council, outlined reasons for drilling the continental crust for scientific purposes and identified four major objectives: (a) Basement Structures and Deep Continental Basins, (b) Thermal Regimes, (c) Mineral Resources, and (d) Earthquakes. Both the Thermal Regimes and Mineral Resources Panels of the U. S. Geodynamics Committee specifically mentioned the SSGF as a desirable target for continental drilling (USGC Report, 1979, p. 97, and p. 118-119).

Thermal regimes are manifestations of the earth's internal heat, the energy source for earthquakes, volcanoes and geothermal areas. The USGC Report (1979, p. 11) states:

> "The Panel on Thermal Regimes identified two major objectives. The first is to produce three-dimensional understanding of heat sources and products of thermally driven processes and to improve the boundary conditions of predictive models. The second is to remove barriers to the understanding of high heat-flow geothermal systems."

Similarly, according to the Mineral Resources Panel (USGC Report, 1979, p. 11),

> "The essential path to finding mineral deposits is to understand how the ore-forming processes have operated in the crust. Many important mineral deposits are concentrations of valuable elements mobilized and transported with energy derived from hot magma (molten rock) driving reactions between aqueous fluids and rocks within the earth. Such centers of magma-geothermal activity may be sampled in depth by drilling in two types of situations: (a) Currently active systems of interest in connection with fundamental principles regarding sources of geothermal energy...(b) Ancient mineralized hydrothermal systems that have yielded significant ore deposits."

In discussing scientific drilling the USGC Report pointed out the advantages of drilling "dedicated holes", i.e., holes drilled solely for scientific purposes, but also encouraged "maximum use of holes of opportunity (holes drilled for specific mission purposes)" (USGC Report, 1979, p. 9). Even though they are expensive, the advantages of "dedicated holes" are obvious. On the other hand, the advantage of "holes of opportunity" is that a large part of the costs is borne by the operator.

Subsequent to the USGC report, the National Academy of Sciences established a Continental Scientific Drilling Committee (CSDC) to provide communication, coordination and advice concerning implementation of a program of research drilling on land. Panels were set up to consider Thermal Regimes, Mineral Resources, Basement Structures and Deep Continental Basins, Drilling Logging and Instrumentation Technology, and Sample Curation and Data Management.

Draft versions of the reports of the first two of these panels were submitted to the CSDC in May 1983 and are currently under review by the National Academy of Sciences and the National Research Council.

The draft report of the Thermal Regimes panel, entitled "A National Drilling Program to Study the Roots of Active Hydrothermal Systems Related to Young Magmatic Intrusions", stresses the importance of Continental Scientific Drilling to society and lists the benefits which might accrue from such a program under the following headings: (1) Volcanic and Earthquake Hazards; (2) Understanding the Formation of Ore Deposits; (3) Radioactive Waste Disposal; and (4) Geothermal Energy. It further considers five main classes of active hydrothermal-magma systems within the U.S.A., i.e.,: (1) Dominantly Andesitic Centers; (2) Spreading Ridges; (3) Basaltic Fields; (4) Evolved Basaltic Centers, and (5) Silicic Caldera Complexes (CSDC, Draft of Thermnal Regimes Panel Report, May 1983). After evaluating various potential sites in the U.S.A., the authors "recommend that a deep drilling program be carried out in a young silicic caldera complex, but that no specific complex be chosen until the requisite preliminary studies and intermediate-depth drilling are completed."

The report continues:

"In addition, we strongly recommend that a program also be developed to take advantage of all available opportunities for add-on investigations in the Salton Trough, and that a broadly based program of geophysical, geological, geochemical, and hydrological studies be carried out in this area, possibly leading to a dedicated deep hole sometime in the future." (op. cit. pp. 7-8).

The draft report of the Mineral Resources Panel also discusses active hydrothermal systems as desirable targets to investigate ore-forming processes. Among the potential sites it considers is the SSGF. The authors state:

"By deeper drilling in the hydrothermal system in the Salton Sea, we would obtain information about the metamorphism of an initially relatively uniform pile of sediments and the consequent changes in porosity and permeability. We might also obtain information about how deeply the brine circulates and whether there are changes in salinity, sulfur, and metal content of the brine with depth. The above information might be obtained most economically through add-on investigations, including deepening of existing or planned industry drill holes, rather than by a program of drilling dedicated holes. The Salton Sea remains the best onshore target for add-on investigations that address the problems of mineral concentration related to spreading centers." (CSDC, Draft of Mineral Resources Panel Report, May 1983, p. 24.)

1.3.2 Development of the SSSDP

On September 27, 1982, W. A. Elders and L. H. Cohen became Principal Investigators on a contract from the Office of Nuclear Waste Isolation to study geothermal systems as natural analogs of possible conditions in proposed nuclear waste repositories in salt. In seeking to obtain suitable samples of brine and rocks for this project they learned that Republic Geothermal, Inc. (RGI) was planning to drill the deepest well yet sited in the SSGF and that the company was sympathetic to the gathering of samples from this well at cost. In consultation with staff of RGI they conceived an ambitious but technically feasible and cost effective plan for an "add-on" experiment in this hole of opportunity. The chief feature of this plan was the deepening of the well from its targeted depth of 12,000 ft (3657 m) to 18,000 ft (5486 m), which is the practical limit of the drilling rigs usually available in the Imperial Valley of California.

Accordingly, they proposed this plan to the CSDC at its meeting on October 22, 1982. The committee responded favorably to the concept and appointed W. A. Elders to chair a steering committee to oversee the development of the proposal and its implementation. A proposal entitled "Salton Sea Scientific Drilling Project, Phase 1" was submitted to the National Science Foundation on November 8, 1982. This initial proposal requested funds to obtain a limited amount of rock and water samples to augment the data to be obtained by RGI in the 3.7 km deep well. This proposal also briefly outlined four subsequent phases of the project. It proposed that in Phase 2 the well would be deepened to 5.5 km with continuous coring. During this stage a much more extensive program of sampling and testing would be carried out, including a fracture stimulation and propping equipment. Phase 3 would comprise the scientific study of this deepened well and analysis of the samples and data recovered from it. If the results obtained warranted, Phase 4 would follow, in which a second well deeper than 5 km would be drilled in another location in the SSGF to further test the characteristics of the deep reservoir and reach higher temperatures. Finally as Phase 5 of the project it was proposed to drill a 6 to 9 km deep well designed to penetrate the magmatic bodies believed to be the heat sources for the field.

These proposals were discussed at an open forum convened by the Thermal Regimes Panel of the CSDC at the Annual Meeting of the American Geophysical

Union on December 8, 1982, in San Francisco. As a result of input received at that meeting, it was decided to proceed immediately by seeking funds for Phase 2 of the SSSDP by requesting an additional appropriation in the FY84 federal budget.

During January 1983, informal discussions were held by W. A. Elders with representatives of the NSF, USGS, and DOE. Concern was expressed in certain quarters that launching a budget initiative to modify FY84 appropriations might lead to resistance as there was the possibility that it could lead to redirection of funds appropriated for and sorely needed by other programs.

For this reason, the discussions in February and March by W. A. Elders and R. W. Rex with these agencies and with the Office of Science and Technology Policy and the Office of Management and Budget stressed the need for an additional appropriation. They made similar representations in discussions with the relevant staffs on the Appropriations Committee and the Science and Technology Committee of the House of Representatives. The key features of their presentations were that the project would be a high-risk undertaking with excellent possibilities for both high scientific and high economic returns. Both pure and applied science would be involved in a collaboration among industry, government, and academia. And, of importance to appropriations committees, the project was promised not to be open ended but to be executed over a short time period and have limited goals, duration, and budget. Bipartisan support was also sought and received from the California Congressional Delegation. Elders submitted the relevant testimony at hearings on the FY84 budget of the DOE. In March RGI submitted a proposal to the Department of Energy requesting $5.9 million for Phases 1 and 2 of the SSSDP. These efforts were successful when at the end of April 1983 the House of Representatives added $5.9 million to the DOE Division of Geothermal and Hydropower Technology for Phase 2 of the SSSDP.

In May, discussions were continued with staff members on the appropriate committees of the U. S. Senate and bipartisan support from the Senators from California was obtained for the SSSDP. Testimony was then submitted to the committee hearings. The joint Senate-House resolution on the FY84 budget of the DOE also provided the additional $5,900,000 for the SSSDP and concurred in the Department's use of available FY83 funds not to exceed $250,000 for the project.

The reason for requesting the $250,000 was to cover the increased mechanical costs of drilling and casing a wider diameter well to 12,000 ft to permit deepening it to 18,000 ft. This cost was initially included in the proposal to the NSF for Phase 1. In keeping with the policy of that agency of supporting science rather than engineering, the NSF requested that the Phase 1 proposal be reduced to delete the cost of this engineering modification.

Parallel to these activities, there were extensive negotiations by RGI and their partners, Parsons Engineering Co., with the Department of Energy concerning their application for a Federal Loan Guarantee of $99.9 million. This is part of the $148 million financial package for the Niland Geothermal Power Plant and Field Development Project, of which the Fee No. 5, the well initially considered for use by the SSSDP, is part. At the end of March 1984 these negotiations were completed and contracts to drill the well in April were finalized.

During 1983 extensive efforts were made to publicize the scientific opportunities that the SSDP would make possible and to invite the broadest participation from the scientific community. Articles about it appeared in <u>Geotimes</u>, <u>Transactions of the American Geophysical Union (EOS)</u>, and

Transactions of the Geothermal Resources Council. It was also the subject of a newsletter (Drilling Early Warning) of the CSDP. Elders delivered talks about it at the Cordilleran Section meeting of the Geological Society of America (GSA) in Salt Lake City in May, and at the Annual Meeting of the GSA in Indianapolis in November. Finally in December the SSSDP was the subject of a half-day symposium at the Annual Meeting of the American Geophysical Union in San Francisco. A draft version of this present report was issued at that well-attended meeting.

Meanwhile the Division of Geothermal and Hydropower Technologies of the DOE was preparing a request for proposals (RFP) to accomplish the drilling activities of Phases 1 and 2 of the SSSDP; the RFP was issued in March 1984. This RFP broadened the potential scope of the SSSDP by inviting competitive bids to drill or deepen wells for the research purposes of the SSSDP within the "Salton Sea Geothermal Area", the latter being defined as those KGRA's in the Salton Trough in which temperatures of 300 C (575 F) could be expected at depths of less than 12,000 ft. (3.7 km). It also allowed that the cost of drilling a well to reach the "initial depth", at which 300 C would be reached, could be included in the proposal. The aim is thus to deepen from this target "initial depth" a further 6000 ft. (1.8 km) to the final "target depth".

As can be seen in Figures 1-4 and 1-10, the depth of the "initial temperature" of 300 C is reached as shallow as 1 km for a well such as Elmore No. 1 near the center of the thermal anomaly. However, on the flanks of the SSGF, in the vicinity of the Fee No. 5 well to be drilled by RGI in April 1984, the depth to 300°C is likely to be more than 3 km (10,500 ft). Thus there are considerable advantages to the SSSDP in drilling near the center of the SSGF, unless a larger part of the cost of drilling to the initial depth on the margins of the field is cost-shared by the operator.

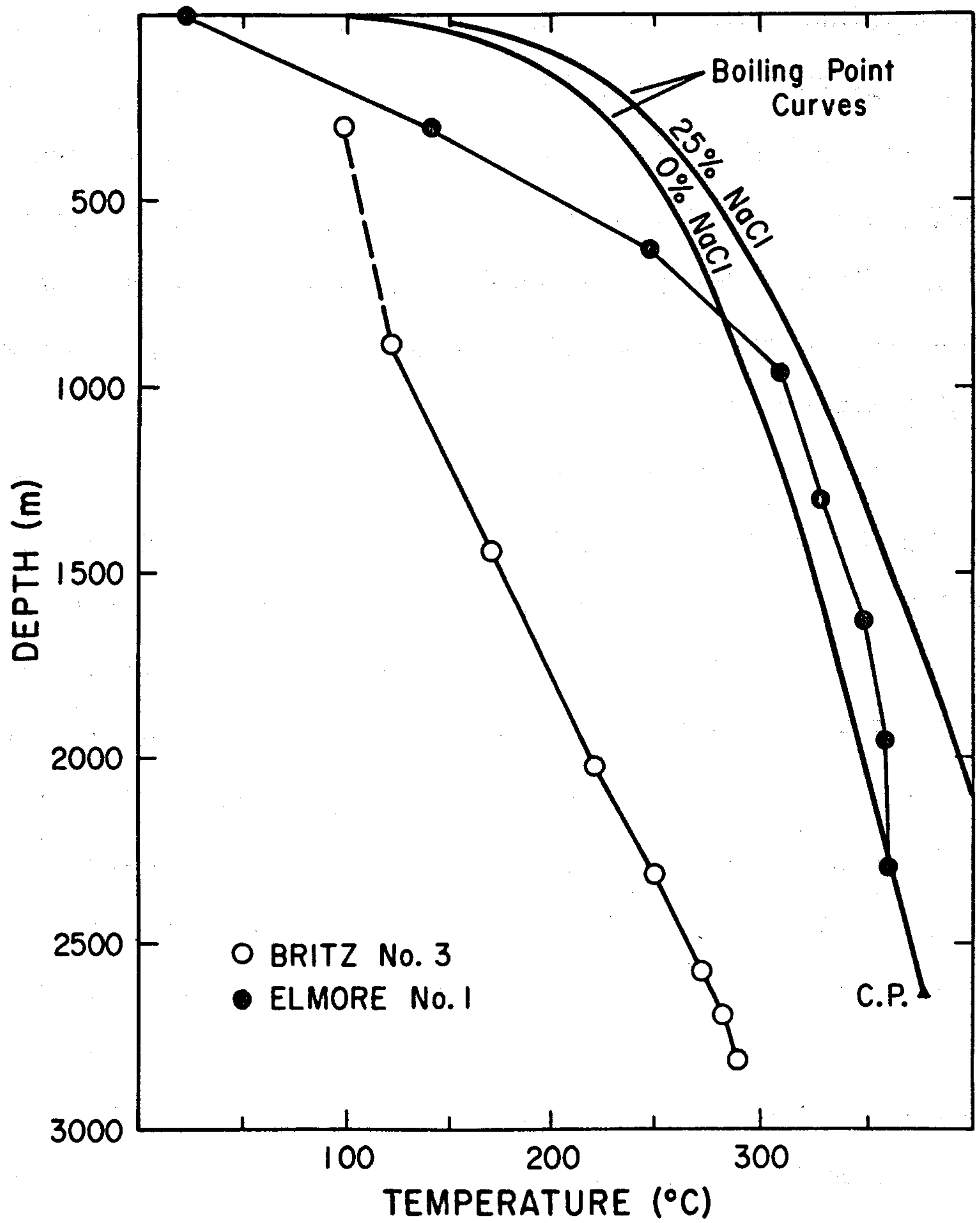

Figure 1-10. Equilibrium Temperature Logs for Elmore No. 1 and Britz No. 3 Wells, Together with the Boiling Point Curves for Pure Water and a 25% NaC1 Solution.

CP = critical point of pure water (Source - Ellis and Mahon, 1977). Figure reproduced from Elders & Cohen (1983).

1.3.3 Scientific Issues to be Tested in the SSSDP: Phase 2

1.3.3.1 Spreading Ridges

By far the most important thermal regimes on earth are mid-ocean rift systems. Recent work suggests that the total heat flow through all the ocean rift systems amounts to about a quarter of the total internal heat flow at the earth's surface (Sclater et al., 1980). The discovery of widespread intense submarine hot springs on the East Pacific Rise is one manifestation of this activity. It is estimated that such hydrothermal circulation drives a volume of sea water equal to the total volume of the oceans through the mid-ocean rifts in about 10 million years (Edmond et al., 1979). These hydrothermal systems at sea-floor spreading centers are important scientifically because they have profound effects on the chemistry of the oceans. Also we now recognize that certain hydrothermal ore deposits, now found on land as the result of plate tectonic activity, were initially formed at such rifts.

Such oceanic hydrothermal systems are new and exciting targets for oceanographic research. However there are obvious cost advantages to studying these systems on land in the few instances where sea floor spreading centers affect land masses. The only opportunity for such a study in North America is in the Salton Trough, the landward extension of the Gulf of California. The Salton Trough appears to be in every way similar to the Gulf of California except that it has been partially filled by sediments of the Colorado River. The Gulf of California is, in turn, a region transitional between the sea-floor spreading system of the East Pacific Rise and the southern end of the San Andreas Fault Transform System. The Gulf contains numerous depressions such as the Guaymas Basin, where sea-floor spreading is occurring and submarine vents discharging hydrothermal brines at 350°C have been observed (Lonsdale and Elders, 1981).

These basins are connected by faults which continue north into the Colorado Delta and merge into the San Andreas Fault System.

The Salton Trough is the site of numerous geothermal fields, now being developed for electrical power production. It also contains young volcanoes at Cerro Prieto, Mexico, and at the Salton Buttes, California, and is subject to frequent major earthquakes and earthquake swarms. According to one recent hypothesis these earthquake swarms may be produced by intrusions of magma into the sediments; indeed the most likely source of heat for the larger geothermal fields is large gabbroic intrusions at depth (Elders et al., 1984). In most of the geothermal fields basaltic dike rocks have been encountered in drillholes. The largest geothermal fields also have gravity and magnetic anomalies consistent with the presence of partly cooled gabbroic intrusions 6 to 8 km below the surface (Elders et al., 1984). The largest and hottest of these geothermal fields, with the largest gravity and magnetic anomalies in the Salton Trough, is the SSGF.

1.3.3.2 Geothermal Energy

For more than a decade many earth scientists have enthusiastically discussed the concept of deep drilling to penetrate bodies of molten rock and zones of convecting groundwater above them. Penetrating such hydrothermal-magmatic systems could unlock enormous sources of energy. However an experiment to drill into an actual magma chamber at depth would require extensive technological improvements to drill into such a hostile environment (temperatures exceeding 1000°C at more than 6 km depth). Some preliminary cost estimates suggest that to successfully drill into a deep magma chamber, even in a favorable environment such as a young volcanic terrane, might cost more than $100 million and require ten years of development work. The SSSDP, on the other hand, is a demonstration of the art of what is possible with off-the-shelf technology.

The first three phases of the SSSDP are only preliminary steps on the way to that long-term goal of exploring a hydrothermal-magmatic system. Wells likely to be drilled or deepened as a result of the RFP currently being issued by DOE are not expected to reach a magma chamber (if any) at the depth likely to be reached. The aims are to explore closer to the heat source and the roots of a hydrothermal system, to look for possible zones of discharge where hot water is rising or possible zones of recharge where colder water is descending to be heated by the magma at greater depth, and to obtain samples of rock and water which will be used to interpret geophysical data obtained at the surface. These data will be used to model the three dimensional structure and hydrology of the whole field. This in turn will help us to better define deeper and hotter future exploration targets in the Salton Sea Geothermal Resource Area. The experiment will also help develop the necessary technology and experience of drilling and producing hot fluids from wells which are deeper and hopefully hotter than those currently drilled by the geothermal industry.

The well will yield more samples and data to the public domain than are available from any commercial geothermal well yet drilled in the Imperial Valley. The deepened well should provide samples from a unique pressure/temperature environment never before investigated directly anywhere in the world. It may explore for permeable zones at temperatures never before exploited in geothermal systems. If funding permits, it could test the possibility of creating fractures artifically and propping them open to generate permeability in the indurated rocks believed to exist at depth.

According to an estimate published by the USGS in 1979, the reservoir volume of approximately 116 km^3 explored by drilling to that time, and having a mean temperature of 330°C, had an energy content of about 1×10^{20} Joules. Assuming a porosity of 20% and assigning reasonable factors for recovery and thermal efficiency, they estimated the electrical power potential of the SSGF to be 3400 MWe for 30 years.

Although drilling the SSSDP well will be considerably more expensive than drilling the shallower wells used in making the USGS estimate, it could have a significant impact on the economics of the SSGF. The production intervals for the wells used in the USGS estimate lie between only 1300 and 2100 m depths. If the combination of permeability, enthalpy and cost encountered in drilling the deeper well anticipated in the SSSDP proves favorable, then the volume of the known resource would be increased by a factor of 5 or more. This could in turn provide a major incentive to overcome the technical and economic barriers to developing this source of energy.

Recently, suggestions have been put forward that at high enough temperatures and pressures a "superconvecting regime" may exist. According to this hypothesis, near the critical point of water it is postulated that the ratio of buoyancy to viscosity increases by a factor of a thousand, which would cause very high fluid flow rates and efficient heat transfer. Such "superconvection", if it exists and could be exploited, would have a revolutionary impact on the economics of geothermal power production. As an example, deepening a well in order to reach supercritical fluid at several times the cost of a conventional well would be economic if it produced at a rate considerably greater than that of the conventional well.

Although superconvecting regimes have not yet been encountered in nature, the temperatures and pressures in the SSGF come closer to the critical point of pure water than in any other field known to us. The critical point is, of course, elevated in temperature and pressure by the higher salinities in the SSGF, making it unlikely that supercritical fluids could exist except at very great depth. However, steep temperature gradients are observed in the SSGF. Linear extrapolation of temperature gradients such as those shown in figure 1-10 suggests temperatures in excess of 400 C should be reached in the SSSDP drilling. Although decreases or even reversals of the temperature gradient are always possible, or even probable especially for a well on the margins of the field, if decreases in salinity are encountered with increasing depth, there is the exciting but remote possibility that conditions approaching supercritical might be encountered for the first time in nature.

Earlier studies (Helgeson, 1968) showed that, to a depth of 2 km (7070 ft) in the center of the SSGF, there is a progressive increase of salinity with depth. Reversals of the salinity gradient with depth would be likely, however, given the postulated environment -- that the source of the dissolved salts is evaporites in the shallow sedimentary section, and that the source of the heat is magmatic intrusions in the basement. If the postulate is correct, we might expect dense, cooler, saline brine to sink as it is displaced by less dense, hotter and less concentrated brine. The discovery of such a less saline, hotter brine, if producible in commercial quantities, could do much to improve the economics of deeper drilling to develop the resource.

1.3.3.3 Understanding the Formation of Ore Depoits

A further important aim is to explore more deeply one of the most saline geothermal fields in the world, where brines contain more than 25% of dissolved salts. Salinity-controlled density gradients can permit very high temperature gradients because they inhibit thermally-driven convection. These brines contain very high metal contents and are actively precipitating copper, lead, zinc and silver ores. Their study should provide considerable insight into ore genesis in hydrothermal systems.

Recently, an estimate of the potential for minerals recovery from these brines suggested that the value of dissolved metals exceeds that of the potential power production (Maimoni, 1982). A 1000 MWe plant, selling electric power at 6 cents/kWh, would earn $394 million a year. This plant would require a brine flow rate of 45 million kg/h. Assuming 90% of the mineral values would be recovered, the market value of the metals produced would be between $500 and $1,500 million a year. The wide range reflects the uncertainties about the content of noble metals. The estimate excludes lithium since the potential production from SSGF could be an order of magnitude greater than 1980 total world sales. The plant could supply 14-31% of the U.S. demand for manganese, a strategic mineral. The brine could also potentially constitute the largest reserve of platinum in the U.S.A. In spite of the large value of the metals in solution, it is by no means clear that techniques currently available to recover them would be economic at present. Once more, however, if deepening the SSSDP well helps to prove that the volume of concentrated metal-rich brine is larger than currently believed, then the incentive to overcome these technical problems will be even greater. Some preliminary unpublished work suggests that these metal-rich and sulfur-poor hypersaline chloride brines may underlie an area of 1000 km^2 in the Salton Trough (Elders and Cohen, 1983).

Within the SSGF, studies of ore minerals have shown that ore deposition is active and pervasive. Early-formed diagenetic iron sulfides are overprinted by hydrothermal and metamorphic sulfides. Currently, saline brines are in equilibrium with oxidized vein assemblages of hematite, sulfides, anhydrite and silicates. At an earlier stage conditions were more reduced, causing formation of pyrrhotite. It is highly desirable therefore to obtain samples from higher temperatures and pressures to study the development of the metamorphic ore body.

1.3.3.4 Radioactive Waste Disposal

The direct measurement of how hot water moves through rocks and the kinds of water-rock interactions involved in such phenomena have immediate and direct application to our understanding of the problems of migration and dispersal of radioactive elements. A likely candidate for the host rock for a mined repository for hot nuclear waste is salt, which occurs as beds or domes in various sedimentary basins in the U.S.A. The temperatures already found in the SSGF equal or exceed those predicted to occur in such a waste repository. With this in mind, the Office of Nuclear Waste Isolation has funded Drs. Elders and Cohen in a four-year project at UCR to study geothermal fields as analogs of possible behavior in the near field of a waste repository (Elders and Cohen, 1983). They are studying the extent to which naturally-occurring radioactive elements, and other elements which are geochemically similar to those occurring in nuclear waste, are transported or retarded as hot brines move through sedimentary rocks. The data obtained will be used to test and validate computer codes which will be developed for modeling the near-field behavior of a waste repository in salt and of clay-rich backfill materials and seals. The samples of rocks and brines obtained in Phase 1 of the SSSDP will be used extensively in this project.

1.3.3.5 Volcanic and Earthquake Hazards

Five small extrusive rhyolite domes occur at the south end of the Salton Sea. A single K-Ar age on the westernmost dome, Obsidian Butte, gave an age of approximately 16,000 years. Similar rocks have been encountered in several geothermal wells near the center of the field. Basaltic rocks occur as xenoliths in the domes and as subsurface dikes, sills or flows in at least five of the wells in the field. One such basalt or diabase occurs at a depth of 8600 ft (2620 m) in the Fee #1 well.

Volcanic hazards are not a prime reason for carrying out the SSSDP. However, the SSGF lies in one of the most seismically active regions of the conterminous U.S.A. (Johnson and Hill, 1982). There have been 12 earthquakes of modified Mercalli intensity greater than VIII in the Salton Trough this century. The SSGF lies a few kilometers west of the apparent southern terminus of the fault mapped as the San Andreas fault in the northern part of the Salton Trough. The SSGF is also part of the zone of frequent earthquake swarms which occur every two or three years in the central Imperial Valley along the Brawley Fault Zone. In June 1981 one event in a swarm with epicenters in the SSGF had a magnitude (M_L) of 5.0 (Elders and Cohen, 1983).

Two different models have been proposed to explain this swarm activity (Johnson and Hill, 1982). The first proposes that local spreading between offset strike-slip faults is taken up by emplacement of dikes parallel to the regional principal horizontal stress. In the second model the swarms are inferred to be triggered by episodic creep events at depths of 3 to 6 km which induce redistribution of interstitial fluid pressure; this in turn induces shear failure. These processes have important implications for the study of geothermics. Changes in fluid pressure cause fluid flow while brittle deformation generates fracture permeability and enhances fluid flow. Recovery of core and fracture mapping will allow the study of the history of fracture opening and sealing in this system and the state of stress, as well as the mechanism of emplacement of dikes encountered.

2. GEOPHYSICS

2.1 INTRODUCTION

Geophysical experiments can be used to support the principal objectives of the SSSDP described in the Introduction, through the direct and indirect measurement of a variety of physical contants associated with the hydrothermal system. Physical constants such as density and temperature constitute direct model parameters for the hydrothermal system, while others such as elasticity and resistivity can be used to constrain or estimae other parameters.

Specific objectives of a SSSDP geophysical experiments program should be to:

(1) Determine the location, extent and nature of the thermal source(s). Experiments to distinguish between magma chambers and dike swarms are particularly important. Characterizing the extent and magnitude of the thermal anomalies and then interrelationships will provide information on the source as well as the pattern of hydrothermal circulation.

(2) Characterize the crustal stratigraphic sequence and its spatial heterogeneity in the general vicinity of the hole drilled for the SSSDP. The sequence is considered to contain a crystalline basement of presumed oceanic affinity overlain by an "upper" basement of metamorphosed sediment. This crystalline basement appears to be at a depth of 5 km (16,000 ft) beneath the SSGF (Frith, 1978). If the depth of the SSSDP hole is adequate to penetrate into this basement, a major geophysical goal would be achieved. Above the metamorphic basement are the geothermal reservoir rocks which may be stratigraphically divided into more than one hydrothermal circulation zone.

The reservoir is overlain by a caprock of relatively impermeable rock above which are recent, relatively unconsolidated sediments. Local faulting and magmatic injection, together with horizontal changes in thermal regime can be expected to provide lateral heterogeneity to the stratigraphic sequence.

(3) Investigate the fracture characteristics and general physical properties of the reservoir rocks. Important questions concern the location, orientation, density, and interconnectedness of fractures, as well as their relationship to the local transform faults and zones of crustal extension.

Geophysical data which are required from these experiments include:

(1) Three dimensional seismic wave velocity and attenuation about the SSSDP hole. Both P and S wave data will be useful. In addition to direct arrivals, secondary phases can provide information on deep layering or structures distant from the well.

(2) Material properties including density, elasticity, electrical resistivity, magnetic susceptibility and thermal conductivity/ diffusivity.

(3) Borehole temperature and surface (conductive) heat flow.

(4) Microseismicity, geothermally induced seismic noise and acoustic emissions. Sources may be either natural or well-induced (e.g. during fracture stimulation).

This section considers geophysical experiments which address these data needs and specifically support the scientific goals of the SSSDP, and as such must be considered to have higher priority than those experiments which either focus on validating generalized, pre-existing geophysical concepts of hydrothermal systems, or simply require access to high temperature/pressure/ corrosive environments for testing of instruments or techniques generic in nature. However, it is not the intention of this document to rule out experiments within these latter two categories, but rather to establish priorities based upon the limited time of access to the well and available resources.

Relevant geophysical experiments are of three types -- those which use surface instruments in the vicinity of the well, those which deploy instruments downhole, and those which make use of the core in the laboratory. Surface measurements can be made at any time; they are discussed in the next section in terms of "regional" and "local" geophysics, based upon the extent of the subsurface investigated. In the second section, borehole experiments, which must be made within the time frame of the SSSDP, are subdivided into geophysical logging (methods which characterize the physical properties of the well bore) and far field geophysics (methods which characterize the subsurface away from the well). Finally, a third section deals with some measurements on the core. Other measurements on the core, having geophysical significance, are discussed in the chapters on Tectonics and Rock Mechanics and Geohydrology.

2.2 SURFACE GEOPHYSICAL EXPERIMENTS

Surface geophysical measurements do not require the use of the well, and as such are not tied to the drilling and ultimate production schedule of the SSSDP; thus they are of lower priority than mission-oriented experiments requiring downhole instrument emplacement.

Regional geophysical studies are primarily useful for characterizing the tectonic framework of the Imperial Valley and SSGF. Local studies can be used in conjunction with borehole experiments to characterize physical parameters in the SSGF and around the well, which will be useful in constraining the thermal source, developing models of hydrothermal circulation and establishing relationships among hydrothermal systems of the Salton trough.

2.2.1 Regional Studies

Geophysical studies of the Salton trough and SSSGF are extensive. The Salton trough and its offshore conterpart, the Gulf of California, are dominated by "leaky" transform faults and tensional zones developed at the ends of right-lateral, strike-slip faults (Elders and Biehler, 1975). The trough has steep, step-faulted margins and a relatively flat basement floor beneath a cover of sedimentary rocks 6 to 10 km thick in the center of the Imperial Valley (Biehler et al., 1964; Elders et al., 1972; Fuis et al., 1982). The transform faults and tensional zones are sites of high seismicity. Intermediate magnitude mainshock and associated aftershock sequences produce right-lateral, strike-slip faulting, while frequent earthquake swarms reflect zones of tension, probable magma or fluid injection, and elevated temperatures (Johnson and Hill 1982).

Surface wave dispersion (Thatcher et al., 1971) and Bouguer gravity (Biehler, 1964) suggest a thin, isostatically compensated crust of ~ 20 km beneath the Imperial Valley, reflecting ductile thinning and a probable "oceanic" affinity (Elders et al., 1972). Simultaneous inversion of gravity and teleseismic travel time data (Savino et al., 1977) support the suggestion of a thin crust beneath the Imperial Valley, and in particular beneath the SSGF.

A comprehensive seismic refraction survey of the Imperial Valley has been carried out recently by Fuis et al. (1982). The study delineated seismic wave velocities with good detail to depths of 10 to 16 km in the sedimentary and metasedimentary sequence; the lines were not of sufficient length to provide depths to the Moho. Seismic reflection profiling has not been used extensively in the Salton trough, perhaps due to the high levels of cultural noise and low seismic Q (high absorption) of the surface sediments. Propreitary vibroseismic data do, however, exist.

It would appear that the crustal structure and tectonic patterns of the Imperial Valley are reasonably well constrained and provide a satisfactory framework for the SSSDP.

2.2.2 Local Studies

The geophysical characteristics of the SSGF including the Niland area, are well summarized by Younker et al. (1982) and Elders and Cohen (1983).

2.2.2.1 Gravity

Local gravity maxima are associated with the geothermal fields of the Imperial Valley (Elders et al., 1972). The largest of these maxima is centered on the Red Hill volcano in the SSGF, and is related to intrusion and metamorphism. Station desntiy of the SSGF is on the order of 1 station/square mile. Improving the density approximately ten fold in the vicinity of the SSSDP well will be useful for improving our understanding of the structural/ petrologic environment around the proposed well.

2.2.2.2 Magnetics

Magnetic surveys of the SSGF (Kelley and Soske, 1936; Griscom and Muffler, 1971) reveal the presence of rocks with high magnetic susceptibility and/or remanence at fairly shallow depth, presumably due to shallow igneous intrusions. Cultrual noise may preclude more detailed magnetic definition, although addtional measurements would be a low cost addtion to more extensive gravity work.

2.2.2.3 Seismic Structure

The seismic structure of the SSGF and the region around the well can be investigated from the surface using standard reflection and refraction techniques. Data might hope to delineate low velocity (high temperature) zones, depth to metamorphic and/or crystalline basement, and locations of magma bodies. Due to the poor resolution of reflection studies in the Imperial Valley to date, future such studies may require appreciable non-standard field geometries and data processing methods, and thus should be regarded as generic in nature, i.e., dealing with problems common to geothermal areas in the Imperial Valley.

Seismic refraction has been carried out in the vicinity of the SSGF (Frith, 1978). These data are of higher resolution in the upper 6 km than those of Fuis et al. (1982). One line passes through the proposed well site and provides evidence for hydrothermal alteration and possible magmatic intrusion within the proposed drilling section. It is questionable as to whether more refraction data would substantially improve the models of Frith (1978).

2.2.2.4 Resistivity

Resistivity surveys are used for detecting electrically conductive zones in the subsurface which may be related to increased salinity and/or temperature. Resolution of the surveys generally decreases as the depth of sounding increases. Meidav et al. (1976) used D.C. electrical currents as high as 200 A for sounding to depths of several kilometers in the SSGF. This survey detected a large volume of highly conductive sedimentary rock between the surface and 2 km depth. The highest conductance coincides with the maxima of the gravity and magnetic anomalies in the SSGF, and with areas of inferred high temperatures and salinity (Younker et al., 1982).

Telluric soundings by Humphreys (1978) in the vicinity of the SSGF confirm the basic results of the D.C. resistivity work. Futhermore, low resistivities along the Brawley fault were interpreted to reflect high permeabilities along this zone, while relatively high basement resistivities (depth of 6 km and below) in the SSGF suggest lower connected porosity in the metasediments and/or sheeted dike complex which underlies the reservoir.

Where surface resistivity studies can be demonstrated to provide addtional detail on relative permeabilities/porosities of the basement and reservoir rocks, they should be encouraged.

2.2.2.5 Seismicity

The SSGF is part of the Brawley seismic zone where seismic swarms are frequent (e.g., see Caltech seismic catalogs for southern California). Swarms tend to occur at the ends of active en echelon right-stepping faults, consistent with the hyopthesis that these zones are "pull-aparts." Either dike injection or redistribution of interstitial fluids may account for the earthquake mechanisms.

Imperial County is formulating plans for requiring seismic monitoring of geothermal areas during various phases of development. Opportunities should exist for cooperation between scientists concerned with the microseismicity of the SSGF and the operators of the Niland plant (RGI/Parsons). Microseismic monitoring with a samll-aperture local network, in addition to improving an understanding of the tectonic environment, may be a useful tool for following the development of fractures and inferring directions of stress during well stimulation experiments (Dennis et al., 1983).

2.2.2.6 Temperatures and Heat Flow

Temperature and heat flow are covered in Section 1.2.3 above.

2.3 BOREHOLE EXPERIMENTS

Downhole geophysical experiments will add an important "third dimension" to the extensive surface geophysical data base already in existence. The data can be tied directly to the results of the downhole geochemical, geomechanical and geohydrological studies. Geophysical methods can provide physical properties of: (1) well and formation fluids, (2) borehole wall, and (3) the subsurface around and below the well at distances of a few borehole diameters to several kilometers.

Geophysical experiments related to the mission of the SSSDP and requiring use of the well must be given highest priority because of the limited time of access to the well. Also downhole data are expected to be of higher resolution than data from surface methods and can be more directly correlated with all other kinds of subsurface information, including measurements made on the core. The recovery of core represents an appreciable investment by the SSSDP.

Borehole geophysical experiments involve the use of instruments downhole. Thus, it is important to emphasize the fact that measurements can be constrained by a variety of borehole conditions such as ANSI swab gate diameter, hole diameter, integrity of the sidewall, and most importantly, the presence of corrosive fluids at high temperatures and pressures. Temperatures in the SSSDP hole are required to be 300°C at < 3.7 km and will probably be higher at the bottom. Thus without insulating, cooling, or heat-sinking the instruments, or cooling the holes, some experiments may be impossible or restricted to the upper portions of the hole. Furthermore, unless new cable technologies are employed (e.g. sheathed thermocouple wire) experiments will be constrained by the 250-300°C upper limit of currently available logging cable. Experiments will have to consider the fact that time constraints on the SSSDP will probably not allow for the development of radically new instruments.

2.3.1 Geophysical Logging

Downhole experiments which provide data on in-situ properties of the well bore fluids and wall are broadly referred to as geophysical logs. Geophysical well-logging has been a staple of the petroleum and geothermal industries for many years (Telford et al., 1976). "Standard suites" of geophysical logs are routinely run in most wells during the various stages of the drilling and completion processes. However, the diversity of logging contractors, the wide variety of tools to observe the same physical parameters(s), and the on-going improvements in these tools lead to questions of quality control and calibration of data which must be addresed. The hostile thermal and chemical environment of the SSSDP hole will only exacerbate these concerns.

The value of standard geophysical logging is well established and must be part of the SSSDP. Tools which directly or indirectly sense temperature, porosity, permeability and density would be of most value; hence the following generic logs are important: (1) temperature, (2) gamma, (3) resistivity, and (4) acoustic. However, in order to ensure quality control and meaningful interpretation, verify the claims of logging contractors, determine the appropriateness of various tools and methods, and coordinate in-hole operations, a responsible logging program under scientific supervision must be developed. A description of currently available well logging tools is given in section 6.3.

Temperatures in the well are required for all scientific components of the SSSDP. Geophysically, equilibrium temperatures are required for interpretation of resistivity, seismic wave velocity and attenuation data; the temperature gradient in the upper conductive layers, together with measurements of thermal conductivity, will establish a heat flow for the well site.

2.3.2 Far Field Borehole Geophysical Experiments

Methods to explore the region away from the well using sensors emplaced downhole are less well developed than the well-bore characterization techniques described in the previous section. The desirability of extrapolating borehole geophysical data downward and radially outward from the well bore is now widely recognized in the scientific community, and thus provides an incentive to improve such methods. A variety of methods has been variously used by industry, academia and government laboratories; others are in early stages of development. It is important to encourage the development of far field borehole geophysics, not only the hardware and field methods, but also the software and interpretational techniques for handling the new forms of data and improving the resolution.

The next sections deal with three types of far field geophysical experiments considered to be important to the objectives of the SSSDP. They are not to be regarded as exclusive but rather a guide as to what is both meaningful and feasible.

2.3.2.1 Vertical Seismic Profiling and Microseismicity

Vertical seismic profiling (VSP) is a generic term for seismic methods which involve either source or receiver, or both source and receiver, downhole. With some VSP geometries such as those involving large source/receiver offsets or from hole-to-hole, seismic raypaths may deviate appreciably from the vertical.

The advantages of VSP methods for subsurface characterization have been discussed by Galperin (1974). By placing sensors in boreholes, seismic surface wave noise is greatly attenuated and complexities in wave propagation due to the weathering zone (statics effects) are largely eliminated. Malin et al. (1982) report distinct arrivals at geophones emplaced in a 700 meter deep well from single vibrator sweeps ~ 30 km from the well head. Leary and Henyey (1983) suggest a VSP travel-time method for fracture characterization about a well using surface sources distributed radially and azimuthally about the well head. Dennis et al. (1983) have observed microearthquakes down to M = -3 due to hydrofracturing at a distance of ~ 1000 meters from a geothermal well at Fenton Hill. Finally Huang and Hunter (1980) report on the use of hydrophones to record tube waves generated in boreholes by seismic waves impinging on fractures which intersect the well bore.

In the SSSDH a high temperature, lockable, three-component geophone sonde can be positioned at a variety of depths in the well to record direct and reflected rays from surface sources and/or sources emplaced in a nearby well. The travel time data will provide information on stratigraphy, lateral heterogeneity, fracture characteristics and zones of elevated temperature. Amplitude and full particle motion data, if available, can be used to estimate Q (attenuation) and investigate anisotropy. Thus VSP will be useful for heat source characterization. Elevated temperatures at depth in the well will probably preclude VSP measurements at depths greater than 3000 meters unless the hole can be cooled below 300°C.

Finally, the same sonde, preferably with wide band sensitivity, can be used to detect microearthquakes and acoustic emissions, either natural or induced. If data are recorded with wide dynamic range, spectral information can be recovered and applied to source studies.

2.3.2.2 Electrical Resistivity and Self Potential

The in-situ electrical conductivity of rocks in a hydrothermal regime provides information on the temperature, salinity and state of the pore fluids. In conventional surveys the conductivity at depth is inferred from D.C. resistivity or electromagnetic measurements made at the surface. Measurements of the electrical properties downhole, employing both two-and four-electrode configurations, will provide the control necessary to interpret surface electromagnetic surveys and downhole electrical resistivity logs. With a borehole, two types of experiments can be carried out that greatly increase the quality of the conductivity measurements. First, with standard in-hole devices, the conductivity adjacent to the hole may be measured, and second with a source on the surface and a sensor in the hole, the conductivity distribution beyond the bottom of the hole may be inferred with far better resolution than can be obtained from surface measurements.

For investigating the thermal regime in the SSGF, a more precise knowledge of the conductivity below the bottom of the hole would be very valuable for detecting the existence of a deeper magma body or generally assisting in the extrapolation of the bottom hole temperatures and would thus assist in locating the major thermal source for the SSGF.

2.3.2.3 Borehole Gravity

It has long been recognized that measurements of gravity at different depths in a borehole can be used to calculate an average value of in-situ bulk density of the medium over a large volume surrounding the hole (Smith, 1950; Hammer, 1950; McCulloh, 1966). Such data, particularly in a layered system such as the SSGF, provide a basis for the downward continuation of surface gravity, assist in the interpretation of seismic data and provide a means of investigating lateral heterogeneity around the borehole.

The potential uses for and feasibility of constructing a high temperature gravimeter have been addressed by Hearst et al. (1978) and Baker (1977). With proper regard for thermal control, Baker (1977) estimates that a borehole gravimeter capable of deployment to 350°C and 18,000 psi in a 7 inch diameter well could be constructed. The time for or cost of development is not known. Current instruments have a capability of 125°C and 15,000 psi. The potential importance of a borehole gravimeter for work in the SSSDP hole and future deep drill holes strongly argues for its development at this time.

2.4 GEOPHYSICAL MEASUREMENTS ON CORES

The sections on Tectonics and Rock Mechanics and Geohydrology describe most of the important physical property measurements that should be made on the core to assist in the interpretation of the geophysical data. They include: bulk density, thermal conductivity, elastic constants, electrical resistivity and magnetic susceptibility.

A careful study of the magnetic properties of the core including susceptibility, magnetic mineralogy and natural remanent magnetization (NRM), in conjunction with the geochemical results, can provide the framework in which to interpret the regional magnetics of the Imperial Valley. Quantifying the magnetic mineralogy through the use of rock magnetic methods (i.e. Curie points and hysteresis parameters) may, in turn, provide information on water/rock interactions and ore-forming processes.

3. GEOCHEMISTRY AND PETROLOGY

In active geothermal systems, metasomatism caused by circulating hot fluids dictates a continuum of significant investigations ranging from that which might be classified as "pure" geochemistry, to economic mineralogy, hard rock petrology and, in the SSGF, soft rock petrology. Distinctions between geochemistry and petrology are thus artificial and will not be made here.

3.1 MAJOR PROBLEMS TO BE ADDRESSED

These are covered in detail in section 1.3 of the Introduction, but here an even briefer outline (Luth and Hardee, 1980, p. 36-7) of the broad questions is repeated:

- o What underlies the 350°C hydrothermal regime (temperature, fluid composition, metamorphic [and ore] mineral assemblages, density, porosity, permeability); and does the subhydrothermal region affect the near surface geothermal system and relate to thermal sources at depth?
- o To what extent is deep-seated (>3 km) hydrothermal circulation important in recharge and chemical alteration of the near-surface geothermal system?
- o Do systems near the critical point of the hydrothermal fluid have distinctive physical and chemical properties that are important in terms of mineralogic reactions and the generation of fluids akin to ore-forming fluids?
- o Is the Salton Trough underlain by continental or oceanic (or both) crust?

- o Are basaltic dike swarms emplaced along 'leaky transforms' the heat source driving the geothermal system(s)?
- o What is the relationship of surface volcanic phenomena (rhyolitic) to the postulated subsurface (basaltic) source?

Additionally,

- o What is the origin or source regions of trace metals in Salton Sea Geothermal System hydrothermal solutions?
- o What are the mobilization and precipitation mechanisms of economically important trace metals?

To these questions are added those of geothermal resource assessment and questions posed by times and temperatures of radioactive waste disposal that cannot definitely be answered in the laboratory but might be answered by experiments that nature has performed in the SSGF.

Geochemistry and petrology is the subject of most of the above questions and is a major contributor to resolution of the other questions. Geochemical and petrological investigations, therefore, occupy the central position in the scientific investigations for the SSSDP.

3.2 SAMPLES AND SAMPLING COSTS

Published geochemical and petrological (henceforth abbreviated "GP") investigation in the SSGF, like many other investigations in privately developed geothermal fields, have, apart from the pioneering work of Helgeson (1968), mostly been <u>post hoc</u> and have often been a demonstration of clever geological detective work and subsequent interpretation. For the most part, the rock samples released to the public domain have been drill cuttings and a few pieces of core. Since these samples were usually released long after a well was drilled, or even abandoned, they were "no cost" both to the operator and to the scientist. Indeed, chips are routinely recovered in drilling; but the paucity of core in the public domain suggests that industry has chosen to put little incremental money into such sampling.

Water samples in the public domain, again, are usually low-budget items -- but in the SSGF, there have rarely been any publically available. When collected, the operator is usually flowing a well for testing purposes and as a courtesy might allow collection of a sample. Although the details of collecting a representative sample of fluid at the surface are complex because of flashing and scale deposition, the equipment to perform such sampling is relatively inexpensive (provided the operator has installed a water-steam separator) and personnel times are not great. Ideally the fluids in the well should be kept from flashing prior to the sampling port. Unfortunately, few wells can be produced spontaneously without flashing in the bore. Separate samples commonly must be taken of gas and liquid fractions that were separated at one or more given pressures, and the analytical results must be mathematically combined in the proper porportions to represent the initial fluid before flashing. This adds complexity and uncertainty to the geochemical interpretation process. Additional uncertainty arises from the possibility that fluids produced at the surface may come from more than one horizon. The best way to overcome this uncertainty is to use a downhole sampler to obtain fluids at a given level in the well where there is known influx of fluids, or from a portion of the well that has been isolated by packers.

In spite of the above complexities, a great amount of geochemical and petrological information can be obtained from samples that are obtained inexpensively -- from no additional cost in the case of drill chip recovery to low costs for surface fluid collection. All of the SSGF geochemistry and petrology in the public domain to date has been done on samples involving small incremental costs of acquisition. As discussed below, a startling amount of new scientific information has been derived from such samples.

Of the routine GP sampling procedures that are expensive, coring is probably the most expensive. The deeper the horizon from which core is taken, and/or the more difficult the drilling, the more expensive the core. A routine oilfield sampling technique of less cost than coring is drill stem testing to obtain formation fluids. Unfortunately, few drill stem tests are successful in hot geothermal wells.

Rarely used, nonconventional, or experimental sampling techniques may produce addtional, valuable information; but the incremental costs and risks to the hole must be balanced against the improvement in quality of information. For example, downhole pressurized fluid samplers have the potential for better answering questions that surface samples do not, particularly if the sampler neither leaks nor sucks fluid into it, but such samplers are only experimental for the upper temperatures expected in the SSGF drill hole.

This section on GP is prefaced with these remarks so that the reader constantly keeps in mind a distinction between obtaining samples for a purpose and obtaining samples because it can be done. There is no such thing as a sample that will satisfy everyone's purposes; samples thus have to be taken with a purpose in mind unless they involve no incremental costs, as is the case for drill chips.

3.3 STRATIGRAPHY AND ROCK PROPERTIES AS A FUNCTION OF DEPTH

With depth in the SSGF, the sediments of the Trough become progressively more indurated and metamorphosed, and at depth are invaded by igneous dikes. These petrological characteristics control the "caprock", formation of secondary porosity, cementation and self-sealing, fluid flow, and surface and downhole geophysical responses to gradually changing physical properties.

The parastratigraphic section consists of a sedimentary caprock, underlain by an upper reservoir of slightly altered rocks, beneath which is a lower reservoir of highly altered rocks (see Fig. 1-6). The nature of the sharp transition between reservoir rocks and the clay-rich caprock is apparently a primary sedimentary feature, but the geological conditions causing the change in the nature of the sedimentation remains to be resolved. The caprock performs the service of being an initial seal for circulating geothermal fluids.

With progressive induration and metamorphism originally porous rocks become sealed and fluid flow decreases. That would signal the demise of a productive horizon except for the pervasive fracturing that is a feature of geothermal fields of the Salton Trough. Whether this fracturing is due to large scale tectonic movements, stresses caused by igneous intrusions, expansion by heating of entrapped fluids, other mechanisms yet to be deduced, or a combination of them is yet to be determined. But the history of repeated fracturing and fracture sealing is recorded in veined, indurated rocks brought to the surface by the drill. The interaction of petrology and petrophysics is thus fundamental to the ability to produce geothermal fluids.

The response of downhole logs to progessive alteration and metamorphism in the SSGF and Westmorland fields was examined by Muramoto (1982). He studied dual induction laterologs, induction electrical surveys, gamma-gamma density logs, and neutron logs. As water-rock reactions transformed heterogeneous sediments into characteristic mineral assemblages that vary little between wells at equivalent temperatures, log responses show less variation. The primary factor producing characteristic log responses, he found, was progressive dehydration of clays and their final metamorphism to feldspars. Changes of mineralogy of shales affected log parameters to a greater degree than changes in mineralogy of sandstones. Log-derived salinities were in poor agreement with actual formation water salinity, but trends were detected.

Such correlations of downhole oilfield logs with petrology are essential, and such information will serve as a guide to the selection of logs for deeper parts of the well. Perhaps continued correlation of petrology with logs will lead to more effective logging in geothermal fields developed in sediments.

The change in induration, and therefore density, resisitivity, and seismic velocity is quite apparent in the SSGF. In addition, the usual occurrence is increased salinity of fluids with increasing depth. The magnetic properties and mineralogy of intrusives, and the effect of temperature on their Curie points, are also important components of the geophysical signal. Thus intimate knowledge of the effects of petrology, and of the geochemistry of formation fluids, is necessary for the geophysicist to interpret the data. Since such problems are covered in the section on Geophysics, they are not discussed further here.

3.4 SPECIFIC INVESTIGATIONS

3.4.1 Stratigraphic and Lithologic Investigations

The SSSDP well will be drilled in an area where the sediments were probably deposited in pronounced foreset bedding, as deduced from unpublished vibroseis data. Unpublished analyses at UCR on drill cuttings from the Fee #1 and Britz #3 wells show differing sand/shale ratios, thus mirroring the inhomogenities of deposition picked up by vibroseis.

As noted in Elders and Cohen (1983, paragraph 3.1), there are no published reports on the micropaleontology of wells in the Imperial Valley. Part of the problem might be traced to the lack of recovery of relatively unindurated sediments as drill chips. At Cerro Pireto, however, Ingle (1982) reported the Pleistocene-Pliocene boundary occurs at 2 km depth, based upon drill cuttings.

Micropaleontological study of drill cuttings from the SSSDP well and adjacent wells is certainly feasible and has the possibility of building a true stratigraphy in the area, determining rates of sedimentation, and correlating these with the environment to deduce further features of the tectonic development of the Salton Trough. Unfortunately, examination of soft sediments in the shallower part of the section will require special efforts to obtain the required samples.

3.4.2 Temperature and Time-Temperature Investigations

Borehole temperature logs reflect the current, geologically ephemeral temperatures. If a paleotemperture at a given depth can be ascertained, an apparent long-term heating or cooling trend can be deduced. The most rapid paleotemperature determinations are probably made via fluid inclusion investigations. In the hands of a reliable and geologically knowledgeable investigator, and with suitable material, mineral formation temperatures are readily determined. Indeed, if suitable inclusions are formed in a vein throughout the history of deposition and sealing of the vein, not only are mineral formation temperature trends but fluid composition trends determinable. Such has been done in the SSGF by Freckman (1978). Deduction of long-range heating or cooling on a horizon-by-horizon basis is a most vital piece of information in developing a picture of the geologic evolution of any geothermal field.

Paleotemperatures can also be deduced from equilibrium light stable isotope fraction between coexisting phases. Kinetic factors, particularly at the lower temperatures, may prevent attainment of equilibrium in the time span of an active geothermal system; hence isotopic temperatures are very infrequently obtained <100°C, even under the best of conditions. The inverse problem, that of equilibrium, can be examined if two solid phases or one phase plus water from a specific horizon can be collected and borehole temperature logs are available. Obtaining water from a specific horizon, however, is non-routine.

Determination of partitioning of an element or elements between coexisting phases, or mineral assemblages, can be compared with thermodynamic data and models to obtain temperatures of formation. Most often, however, the temperature is only one (but important) variable in chemical potential-based calculations (e.g. Bird and Norton, 1981). Kinetic factors, again, enter into the attainment of equilibrium; and the presence of water usually promotes the speed of reactions involving solids.

Rates of reaction and the approach to equilibrium enter into many, if not most GP investigations. A time-temperature history at a given point is thus as desirable as it is unobtainable. The extent to which a chemical reaction has proceeded, however, reflects some integrated effect of the time-temperature history on the kinetics of that particular reaction. This integrated time-temperature effect will enter into many discussions below.

3.4.3 Metamorphism of Organic Materials

Organic matter is particularly sensitive to elevated temperatures, so it is natural to investigate the changes in geothermal areas. Barker (1983, 1979) examined the metamorphism of vitrinite, from woody plant debris, in several geothermal fields including the SSGF. Vitrinite reflectance is a function of the degree of metamorphism and is readily determined in the laboratory. Barker

(1983) concludes that after ~ 10^4 yrs, "reaction duration has little or no influence on metamorphism of organic matter in liquid-dominated geothermal systems". This is a conclusion that could be better tested with samples from the SSSDP, and Barker and other investigators have indicated their interest.

The effects of temperatures (and time) on the maturation of petroleum hydrocarbons has recently been a quite active topic of research. In conjunction with the temperature, time-temperature (e.g. vitrinite studies) and the other investigations to be performed on samples from this well, further testing and refining of theories should be possible, especially since the duration of heating is very short compared to normal sedimentary sequences at the same temperatures.

$\delta^{13}C$ and concentrations of hydrocarbon gases up to C_6 were determined by DesMarais et al. (1982) and Truesdell et al. (1982a) for geothermal fluids being produced from the Cerro Prieto field. Along with similar analyses for dissolved gases and associated coal, they interpreted the data to give the status of equilibrium as well as probable sources of the hydrocarbons themselves.

3.4.4 Clay Mineral Stabilities

Clay mineral stabilities are closely tied to diagenesis, so the progressive changes in the clays, assuming that their pre-diagenetic character is ascertained and the reaction fluids are ascertainable or unimportant, may yield additional significant information for students of diagenesis. Muffler and White (1969) found that detrital montmorillonite converts to illite/montmorillonite <100°C, and the latter converts to illite <210°C in two SSGF wells. Further information and references to other work on clay minerals that has been performed in the SSGF is found in McDowell and Elders (1980) and McDowell (1983).

Relevant to some plans for radioactive waste disposal is the question of the stability of clays used as backfill or overpack around waste canisters. The heating times of interest in waste disposal are longer than laboratory times but shorter than heating times deduced for the SSGF. Hence the progressive metamorphism of clays, combined with temperature and time-temperature investigations of the same samples, can be compared with equilibrium or kinetic data from the lab. Hence the kinetics of decomposition or transformation may be more thoroughly understood.

3.4.5 Metamorphism

Diagenesis grades into hydrothermal metamorphism rather quickly with depth in geothermal areas; the depths at which reactions occur in a rather homogeneous section are more dependent upon temperature than upon other variables.

McDowell and Elders (1980) recognized four metamorphic zones in the study of material from the Elmore #1 well in the SSGF: (1) a dolomite/ankerite zone, <190°C, in which mixed-layer illite/smectite also occurs with calcite, hematite, quartz, and sphene; (2) a calcite-chlorite zone at 190-325°C, containing illite/ phengite, quartz, albite, adularia, epidote, pyrite, sphene, sphalerite, and anhydrite; (3) a biotite zone, at 325-365°C, containing vermiculite, talc, quartz, orthoclase/microcline, albite, epidote, pyrite, actinolite, and sphene; and (4) a garnet zone, >360°C, containing andradite with biotite, quartz, albite, epidote, actinolite, pyrite, and sphene.

This metamorphism is ongoing, and the metamorphic formation fluids can be sampled (with greater or lesser precision) by the flowing well. Stable oxygen isotope analyses, combined with models, will give estimates of the ratio of water to rock that has reacted. Kendall (1976) made such estimates for samples from a few wells in the SSGF; Olson and Matlock (1978) did the same for the Westmorland geothermal field; and Williams and Elders (1981) have published such information for the Cerro Prieto geothermal field.

Analysis of radiogenic isotopes (Sr, Nd, Pb) in secondary phases will provide clues for the provenance of cations in the hydrothermal solutions. Bulk rock analyses and comparisons of unaltered and metamorphic materials will be useful for calculations of enrichment/depletion factors of economically important trace metals. Such enrichment/depletion factors, combined with careful mineralogic observations, provide most useful information on the mobilization and precipitation processes of economically important trace metals under various physiochemical conditions.

Synthesis of all of the three-dimensional mineralogic information, isotopic analyses, paleo and present temperatures, textures of the rocks, inferences as to past water compositions from fluid inclusion analyses, and analyses of water presently being produced, combined with all other qualitative and quantitative information, produce an understanding of the chemical/petrologic evolution of the geothermal field. The sparsity of areal information to date on the SSGF has not made this field as ideal for an overall synthesis as the Cerro Prieto field across the border in Mexico. There, since the Mexican government has freely made available cuttings, cores, waters, logs, etc., such an overall synthesis has been attempted. Elders et al. (1984, 1981) have performed mass transfer and heat transfer modelling; Schiffman et al. (1984) have examined metamorphic phase relations and facies; and Bird et al. (1984) have done thermodynamic modelling of calc-silicate mineral reactions.

Using data to be obtained from the SSSDP well, along with existing data in the public domain from the SSGF and any other samples that operators may make available in the future, such an areal and temporal picture can be constructed for the SSGF. Since the SSGF has considerably higher salinities than

Cerro Prieto, comparisons and differences will be even more enlightening than an investigation of the SSGF alone.

3.4.6 Ore Deposition

One of the earlier and most exciting discoveries about the SSGF was that the highly saline fluids deposit ore minerals both in situ and in pipe scales when such wells are produced. Salinities of brines in the SSGF are often similar to those found in fluid inclusions in ore deposits, and the parallelism with the then recently-discovered Red Sea Brines was quickly noted. Pyrite, hematite, sphalerite, chalcopyrite, galena, and pyrrhotite were found in cores; and the siliceous scale contained bornite, digenite, chalcopyrite, chalcocite, stromeyerite, tetrahedrite, and native silver (Skinner et al., 1967).

Subsequent work by McKibben (1979) and McKibben and Elders (1983) extend the exciting nature of these discoveries. These studies have shown that the loci for later ore mineralization due to the onset of the geothermal system were earlier diagenetic sulfides. Replacement textures indicate that the source of metals was the shaley sediments. The occurrence of carbonate-pyrrhotite veins appears to reflect an older stage of metamorphic ore formation in which highly reduced, S-rich fluids were present. The 300°C brines currently sampled from the system are in equilibrium with a hematite-pyrite-Fe silicate assemblage; the redox state may be buffered by reactions involving chlorite and/or epidote. Chloride complexing accounts for the base metal solubilities in the present brines. The deposition of sulfides is now occurring only where S-poor brines gain access to sulfur in earlier-formed iron sulfides (McKibben and Elders, 1983).

Even though intensive study of a limited number of samples had led to the above conclusions, the study of the ores being deposited and the mechanisms for deposition have just begun.

3.4.7 Source of Water, Brine, Metals, and Recharge Area

From stable isotope studies, Craig (1966) deduced that the waters in the SSGF were largely, if not completely meteoric. By combining additional isotopic data with the hydrology of Loeltz et al. (1975), Coplen (1975) extended Craig's work and demonstrated that all the subsurface waters in the central Imperial Valley are partly evaporated Colorado River water. Isotopic study of waters obtained during the SSSDP will extend these studies.

All deep waters in the Salton Trough are primarily NaCl brines that vary up to 280,000 ppm total dissolved solids. Paleo salinities can be deduced for vein material from fluid inclusion freezing temperatues, and such information may thus give a rough trend of salinity during deposition over time.

The ratio of chloride to bromide in water has been used to investigate the origin of salt in these geothermal systems; the ratios range from that found in Colorado River water to that found in ocean waters. Rex (1983) suggests that the geothermal brines are derived from several sources, including local precipitation, fossil lake waters from former lakes formed when the flow of the river filled the basin with brackish water, dissolution of the saline residue from dehydration of these lakes, and waters that have equilibrated with rocks >300°C. Rex's (1983) ongoing study of this problem will be aided by samples from SSSDP.

The source of metals in the brine has been the subject of several investigations. Doe et al. (1966) obtained isotopic evidence that indicated that 80-100% of the Sr and 50-100% of the Pb has been leached from the surrounding sediments. White (1981) arrived at a similar conclusion with regard to Li, B, and NH_3. The sulfur itself has an isotopic composition similar to the meteorite standard (White, 1968), which suggests that it is either magmatic or leached from sediments that are derived from erosion of igneous rocks. The sources of the various metals and the associated sulfur is thus a subject of continuing and vital interest. Since so few documented samples of ores from the SSGF are in the public domain, any samples retrieved during the SSSDP will be of great interest to a number of investigators.

3.4.8 Igneous Rocks

Surface Quaternary volcanic rocks occur in two locales in the Salton Trough. Cerro Prieto volcano, about 30 km south of the Mexican border, is a calc-alkaline rhyodacite; and the five small domes at the south end of the Salton Sea are alkali rhyolote. Basaltic rocks occur as xenoliths in the domes and as subsurface dikes, sills, or flows (Robinson et al., 1976).

The Cerro Prieto rhyodacite appears to be typical of Pleistocene volcanism in the area surrounding the Gulf of California; however, the Salton Sea rhyolites are identical in composition and $^{87}Sr/^{86}Sr$ ratios to soda rhyolites erupted on islands of the East Pacific Rise. The Sr isotopic ratio of the Cerro Prieto volcano is even more primitive, suggesting a depleted mantle source for it, too. Hence the hypothesis that the conditions of magma generation in the Salton Trough are similar to those operating beneath oceanic spreading centers (Elders, 1979).

A rather fresh diabase dike occurs at ~3.9 km depth in Britz #3 well. Other subsurface intrusions are seen in other wells (Robinson et al., 1976). It is therefore expected that dikes will be encountered before the total depth of the SSSDP well is reached. In addition to examining the petrology, geochemistry, and isotopic chemistry of these rocks to test the above hypotheses, investigation of these intrusives will yield more information on mechanisms of igneous intrusion in this type of tectonic environment.

3.4.9 Hydrology of Geothermal Fluids

The knowledge of discharge and rechagre areas of hot and cold brines is of vital interest ot the developer of a geothermal field, for the fluid flow is a major factor in heat transport. What might otherwise have been a mathematically straightforward computation of temperature distribution may become a geologic and geochemical detective story to find out where surface waters enter the system, where they become heated, and where the heated waters go. Reservoir engineering measurements are used to monitor this during the production stage of a geothermal field. Changes in $\delta^{13}C$ in CO_2 also may indicate boiling in the reservoir (Janik et al., 1982) and will thus contribute to the reservoir engineering.

Determining the hydrology of a geothermal system in the undisturbed preproduction stage involves many elements outlined above: determing the origin of high-salinity fluid and some of the individual compoenents; stable isotopic investigations and investigation of radiogenic isotopic and chemical metamorphism of fluids along potential pathways; tritium determinations; determining the origin of dissolved gases; in situ density calculations for the specific brines at each depth; subsurface temperature distributions; surface heat flow and surface discharges; whether fluids are carried by interconnected porosity or by fractures; change in temperatures during a protracted production test; etc. These methods are gaining increasing importance today in the field management stage, also.

Some references to such hydrologic determinations have been made above: Olson and Matlock (1978) for Westmorland, Coplen (1976) for the central Imperial Valley; and Kendall (1976) for the SSGF, but limited in number of available wells. The most comprehensive studies using such an integrated approach to a geothermal field in the Salton Trough have been those for Cerro Prieto (Elders et al., 1981, 1982; Truesdell et al., 1982b), again because samples and data have been made freely available by the Mexican government.

All data obtained from the SSSDP well are expected to contribute to the hydrologic understanding of this geothermal field. It is hoped that private operators will see the value of determining the overall characteristics of the hydrology and will add to the model by allowing sampling of some of their wells.

4. TECTONICS AND ROCK MECHANICS

4.1 INTRODUCTION

4.1.1 Tectonics, Rock Mechanics, and the Salton Sea Hydrothermal System

The tectonics and rock studies activities aid the characterization of the Salton Sea hydrothermal system in providing information on the tectonic setting, which is the major reason the thermal anomaly is there, and in providing physical properties data for interpretation of geophysical and reservoir engineering studies.

The Salton Sea Trough is a structural depression lying along the boundary of the North American and Pacific Plates. This is a complicated region where the mechanism of plate interaction is changing from that of oceanic rifting on the East Pacific rise system to that of the strike-slip motion of the San Andreas fault system. The Salton Trough is one of the few areas of the world where an extensional plate boundary is affecting continental crust (Elders, et al, 1972). Elders (1979) has developed a plate tectonic model of the region consisting of transform faults and pull-apart basins. The basins are associated with spreading centers and are the locus of much geothermal activity. In this model, the spreading centers are offset by transform faults along which strike-slip motion occurs.

Johnson and Hill (1982) note that seismic activity in the Salton Trough is of two types--major earthquakes on the strike-slip faults and earthquakes swarms which occur in "pull-apart basins" as frequently as 2 to 3 years apart. Johnson and Hill (1982) consider pore pressure build-up to be a probable cause for the swarms. The pore pressure build-up may be either due to magma emplacement or to episodic creep along the strike slip faults.

Hypocenters for the Salton Trough seismic activity are shallower than 15 km and most originate at less than 6 km (Gilpin and Lee, 1978), which is the maximum proposed depth for the Salton Sea deep hole. Thus the SSSDP program affords an opportunity to perform geomechanical studies at depths of seismic activity.

4.1.2 Data Needs

4.1.2.1 State of Stress

The state of stress is a key element in understanding the seismicity and tectonics of the Salton Trough. Furthermore, the stress state many be required to understand the metamorphism, particularly if the stresses are not hydrostatic. The Salton Sea deep hole affords a rare opportunity to perform stress measurements at depths of seismic activity. The only direct method of measuring stress at depth in boreholes is hydraulic fracturing; however, the method has not been used under conditions as hostile in temperature and pressure as those expected in the hole. Stress information may be inferred from wellbore breakouts, which may be detected by caliper or televiewer logs, from core disking, or from a variety of core measurements such as differential strain analysis or anelastic strain recovery.

4.1.2.2 Physical Properties

The physical properties of the rock are required for modelling of the hydrothermal system and for interpretation of the geophysical measurements.

For the most part these are measured in the laboratory. Required properties include the strength, deformational characteristics, thermomechanical properties, density, and porosity. In particular, the heat capacity and thermal conductivity of the rock have a major influence on the processes of heat transfer. The state of stress and the strength of rock determine the extent and mode of fracture development. These fractures may be important conduits for fluid flow.

4.1.2.3 Tectonic Inferences from Core Studies

The sediments of the Salton Trough have been derived from deltaic sedimentation of the Colorado River and its ancestors and from alluvial deposition along the margins of the trough. The provenance of the sediments, if known, may yield valuable information on the relative movements of the various tectonic blocks surrounding the trough, particularly if the alluvial sediments are encountered. Petrofabric studies in metamorphosing rocks may provide data on the directions of the principal stresses.

4.2 MEASUREMENTS IN THE BOREHOLE

4.2.1 Hydraulic Fracturing Stress Measurements

The Salton Sea Scientific Drilling Project and its related hydraulic fracturing stimulation experiments provide an opportunity to obtain in situ stress information in a region of considerable tectonic interest and at depths greater than stress measurements have been previously obtainable (with the exception of the Michigan Basin Deep Hole). Description of the hydrofracturing method of determining stress is given in Haimson (1978a).

The stress information will be unique and invaluable for the reasons described below. First, the stress measurements will have considerable tectonic interest. The Salton Sea area is one of transition from the "pull-apart" tectonics associated with the Gulf of California to the strike-slip faulting of the San Andreas fault system. This transition should be reflected in a reorientation of the minimum principal stress from vertical (in the pull-apart region) to the horizontal (in the strike-slip region). The stress measurements provide a basis for testing the use of Byerlee's "Law" of rock friction to determine the stability of a region with respect to earthquake activity as the Salton Sea area should be in a state of "failure". Comparison of the stress information with stress field deductions based on earthquake focal mechanisms should provide an important test of our ability to determine earthquake hazards from stress information.

From the reservoir development standpoint, the transition in minimum stress orientation should have a major impact on the orientations and flow properties of the fractures, as permeability should be greatest along those fractures oriented normal to the minimum stress direction.

The method will be to obtain the minimum horizontal stress from analysis of shut-in pressure records, and to obtain the maximum horizontal stress from the breakdown pressure values. Fracture orientation can be practically obtained only by acoustic borehole televiewer or by microseismic monitoring if the fracture is of sufficient size and nearby observation wells are available.

The difficulties of performing a hydraulic fracturing stress measurement in a deep geothermal well should not be minimized. Packer systems are not generally designed for sealing pressures greater than about 70 MPa or for operating temperatures greater than about 250°C, but these temperature problems may be overcome by cooling the well. The expense of the cooling could be shared with injection permeability tests which would use the same equipment; nonetheless the costs may be substantial. Similary, packer systems may not be capable of providing adequate seals for the pressure required. Haimson and Doe (1983) noted in a 1600 meter well in granite that the pressures required for breakdown were in excess of the capabilities of the pumps and probably nearly in excess of the sealing capabilities of the packers. On the other hand, hydraulic fracturing tests were completed at depths of 5,000 meters in the Michigan Basin where the required surface pressures for breakdown were as much as 62 MPa (Haimson, 1978b). The question of the packer sealing pressure will depend on the stress conditions at the site. The breakdown pressure can be given by the well known relationship (Haimson, 1978a):

$$Pb = 3\,Smin - Smax + T$$

where Smin = minimum horizontal stress
Smax = maximum horizontal stress
T = Tensile strength
Pb = Breakdown pressure

neglecting pore pressure and poroelastic effects. If the stresses are hydrostatic then the breakdown pressure should be approximately twice the lithostatic stress. The pressure required at the surface for breakdown under these conditions would be about 200 MPa, which is considerably in excess of the operating limits of the packer system. On the other hand, if the state of stress is near a failure condition, as the earthquake activity would suggest, then the deviatoric stresses would be higher and the breakdown pressures lower. For example, if the maximum and minimum stresses have a ratio of about 2:1 and a mean of the lithostatic stress value (or about 100 and 200 MPa respectively), breakdown would require about 40 MPa at the surface. Inclusion of poro-elastic factors and pore pressure effects would reduce the breakdown even further.

If the breakdown pressures are in excess of the packer system capabilities, then some stress information may be gained by injection of preexisting fractures and recording the shut-in pressure data (Cornet, 1983). The orientation of the principal stresses may be known approximately if the orientations of the fractures are known from televiewer logs or core.

Stress measurement program options are as follows:

(1) Ideal Program: Ideally stress measurements would be performed at least at 2,000 foot intervals to provide data on the change in stress with depth. The measurements would be made before the casing was set to allow fracture mapping with the televiewer, hence measurement would be made in stages, before each string of casing is cemented.

(2) Practical Program: The measurements at shallower depths would be made through perforations in the casing; measurements below the cased interval would be made in the open hole. Only minimum horizontal stress values would be obtained from the shallow measurements. This program would have advantages over the ideal program in that all the work with the hydraulic fracturing crew could be done at one time.

(3) Minimal Program: The pressure records for the hydraulic fracture stimulation experiments would be analyzed to determine what stress information could be deduced.

Laboratory studies will be required to obtain fracture toughness and apparent strength values. Laboratory simulations can also indicate if fluid invasion into the rock matrix should be considered in the stress measurement analysis.

4.2.2 Televiewer, Caliper Logs, and Detection of Wellbore Breakouts

Wellbore breakouts are enlargements of boreholes which are generally thought to be the result of rock failure in the highly stressed region around the borehole (Zoback, 1983; Bell and Gough, 1983). The breakouts are often restricted to narrow bands on opposite sides of the borehole. The location of the breakouts corresponds with the direction of minimum stress as indicated by hydrualic fracturing measurements.

Borehole televiewer logs or four-arm dipmeter meter logs may be used to detect breakouts and their orientations. Televiewer logs may also be used effectively to obtain hydraulic fracture orientations.

If wellbore breakouts are present in the well, one may infer that the stress concentration around the borehole results from plastic or viscoelastic rather than elastic behavior (Doe et al., 1984). Hydraulic fracturing stress mesurements made under these conditions may not be interpretable using conventional elastic-based theory. The most information that can be gained whould be the minimum horizontal stress magnitude (from the shut-in pressure) and the maximum horizontal stress direction from the fracture orientation.

4.3 MEASUREMENTS ON CORE SAMPLES

4.3.1 Stress Indicators

4.3.1.1 Anelastic Strain Methods to Determine Stress Orientations

Most of the deformation undergone by core after drilling occurs instantaneously as a result of elastic recovery. A portion of the recovery, however, occurs by time-dependent anelastic mechanisms even in relatively brittle rocks like granite. Teufel (1982) has summarized work which has been done to determine the applicability of anelastic recovery methods in determining the orientations of in situ principal stresses. His comparisons of principal orientations of anelastic strain measured on drill cores have correlated well with the directions of horizontal stresses determined from stress measurements in several locations including the Nevada Test Site (tuff) and the Piceance Basin (sandstone).

If oriented core can be obtained from the well, the orientation of the maximum and minimum horizontal stresses may be obtained from the monitoring of lateral strains on the cores. To be successful the cores should be instrumented as soon as practicable after removal from the hole. The recovery should be monitored with the core under constant temperature conditions to avoid spurious thermally-induced stains. Finally, the microfabric should be analyzed after the testing to determine whether or not anisotropic material properties may have influenced the results of the strain recovery. The anelastic recovery may be useful as an independent check of the stress orientations obtained from stress measurements made in the borehole.

4.3.1.2 Differential Strain Analysis

Differential strain analysis (Simmons, et al, 1974) is a stress measurement technique based on the assumption that density of microcracks of a particular orientation is related to the in situ stress. As the microcracks affect the deformational properties of the rock, the strains measured upon reloading under hydrostatic conditions should be related to the stress field orientations (Montgomery and Ren, 1983).

4.3.1.3 Kaiser Effect

The Kaiser effect is the occurrence of acoustic emissions in rock samples which are loaded to stresses which exceed their previous in-situ limits (Kanagawa et al, 1976). Studies of the Kasier effect can be used to approximate the stresses at depth and may be run in conjunction with other tests such as differential strain analysis.

4.3.1.4 Core Disking

Core disking is a fracturing of the core along closely spaced fracture planes that occurs under high stress conditions (Obert and Stephenson, 1965; Obert and Duvall, 1966). Disking can be used only to determine approximately the ratio of the vertical and horizontal stresses.

4.3.2 Laboratory Tests to Determine Physical Properties

It is recommended that laboratory tests of the physical properties of core recovered from the Salton Sea borehole be performed under environmental conditions resembling those encountered in situ. Test should be performed for the following purposes: integration of the surface and borehole geophysics, and investigation of the relationships between fluid permeability, porosity, and rock/water interactions. The work will increase understanding of the in situ thermal regime and permit effective developing of high temperature geothermal resources. Laboratory measurements should include:

- o electrical resistivity (including complex resistivity and phase angle measurements)
- o acoustic velocity (both P and S waves with attenuation characteristics)
- o bulk and pore compressibility
- o thermal conductivity and diffusivity
- o fracture toughness
- o fracture and matrix permeability.

The test apparatus used for the physical properties measurements should be capable of pressure and temperature conditions of 170 MPa and 500 degrees Celsius. At these pressure and temperature conditions geochemical reactions may proceed quickly, particularly when conditions are perturbed from in situ conditions. These reactions may affect physical properties. Pre- and post-test geochemical and petrological characterization of the samples should be carried out to aid in interpreting the results.

Measurements of the electrical properties will provide control necessary to interpret surface electomagnetic surveys and downhole resistivity logs. Measurements of the acoustic velocities and attenuation will provide control in the interpretation of the surface seismic surveys and downhole acoustic logs. The velocities should be inverted to provide a measurement of crack parameters in situ. The bulk and pore compressibility measurements are important for the hydraulic storativity of the reservoir in assessing transient fluid flow. The thermal properties are essential to understanding heat flow in the hydrothermal system. The fracture toughness measurements are essential to interpreting the hydraulic fracturing stress measurements and to assessing the origins of natural fractures in situ. The fracture and matrix permeabilities are required for supporting well test analyses to determine the relative contributions of matrix and fracture flow. It will be important to establish what relationships exist between physical properties of the rock and the rock compositions particularly with respect to fracture and pore filling materials, and the degree of alteration or metamorphism of the rock.

The ratio of the static to dynamic bulk moduli should be a direct function of the crack porosity, as should the ratio of the static and dynamic moduli of the recovered core. A general experiment measuring the dynamic and static moduli together with optical determination of crack densities should yield important information for relating the sonic log data to the porosities in situ.

4.3.3 Structural and Sedimentologic Analysis of Cores

The tectonic history of the Salton Sea area should be analyzed using standard methods of sedimentologic and structural analysis. Where core is available, the composition of clasts, particularly lithic fragments, should be analyzed to determine the sediment sources. Variations in the sediment sources may be useful in deducing the movements of the structural blocks which make up the Salton Trough.

Petrofabric and microcrack fabric analysis of core specimens may be used to determine the evolution of stress conditions. Microcrack fabric may be related to the physical properties of the rock as determined by geophysical logging and laboratory testing.

5. GEOHYDROLOGY

5.1 INTRODUCTION

In a convective-hydrothermal system, various processes take place that influence heat and mass transfer. These processes include source cooling, convective and conductive heat flow near and above the heat source, interactions between the host rock and fluid at elevated temperatures, chemical effects on formation porosity and permeability, interaction of fracture and porous media flow, origin and evolution of the primary fluid conduits, and a host of other processes related to the intrusion of magmas into the upper crust and the development of associated hydrothermal systems. These processes are central to the evolution of the continental crust and its resources. Developing an understanding of the processes is a prime objective of the Thermal Regimes portion of the Continental Scientific Drilling Program. Several important geohydrological experiments should be made in the Salton Sea deep hole in order to insure that this objective is realized. This report reviews those experiments.

The geohydrological data of interest can be classified into the following categories: subsurface thermodynamic data (T,P), rock properties, fracture data, production data, and natural flow data. Before discussing the data needs in more detail, we will first review briefly the hydrothermal setting of the proposed hole.

5.2 SALTON SEA GEOTHERMAL FIELD

The Salton Trough can be essentially viewed as an area of very high regional heat flow produced by crustal extension and rifting modified locally by shallow crustal intrusions and associated hydrothermal circulation. The largest and hottest of these geothermal fields, the Salton Sea Geothermal Field, has large geophysical anomalies perhaps reflecting partly cooled igneous intrusions at shallow depths. This geothermal system has been identified as an attractive target for deep drilling by a number of scientific panels and workshops. Scientific investigations in wells have the potential to provide information about: (a) the local hydrothermal system around the well, (b) the overall SSGF hydrothermal system (to some extent), and (c) the relationship between the geothermal field and the regional setting. The primary scientific objective of drilling the SSSDP hole is based on category (a). The extent to which the well can provide information and insights into the other two categories is uncertain at this point.

5.2.1 Well as an Isolated Observation Point in a Hydrothermal System

The primary aim of the SSSDP is to drill the deepest and/or geothermal well in the world in order to explore the roots of this hydrothermal system. Depending on whether thermal gradients continue rising, decrease or reverse, a host of scientifically interesting possibilities arise. One distinct possiblity is that the deeper part of the well will reveal a region of pressure or temperature never before directly sampled. Observations on the permeability distribution with depth will provide important insights into the deeper parts of the Salton Trough. This information is essential for resource evaluation. Other questions of interest include the origin and evolution of flow conduits, the nature of the vertical hydrologic connectivity, and the remote possibility of encountering a region of superconvection.

5.2.2 Well as an Observation Point Relevant to the Entire SSGF

Observations in this well could contribute information relevant to modeling the three dimensional structure and hydrology of the entire Salton Sea Field. The modeling could help determine the thermal and hydrologic connections between the site where the well will be drilled and other wells in the geothermal field. At shallow depths, a well on the flanks of the thermal anomaly is likely to be intermediate in temperature between that in the central part of the thermal anomaly and the regional regime. One possible hypothesis is that a single heat source located near the center of the field affects both the margin and the center. In that case one would expect a temperature reversal at depth in wells located at the flanks of the system. Such temperature reversals occur as cold fluids recharge the system at depth from outer regions. An alternative hypothesis is that the marginal region represents an independent thermal or circulation system. As such, it would provide an additional example of a hydrothermal system, perhaps of a different age or intensity, to compare and contrast with the main SSGF.

5.2.3 Well as an Observation Point Relevant to Thermal Regime of Salton Trough

Observations within this well may provide direct or indirect information about the heat source of the SSGF and therefore, about the nature and effects of crustal rifting in the Salton Trough. For example, a well in the marginal region could possibly detect a 'stepout' of the zone of active intrusions. In this case, one major contribution would be to gain understanding of this process which clearly must have occurred repeatedly in the region, and thereby gain some understanding into the relationship between the localized geothermal anomalies and the regional thermal regime.

5.3 DATA NEEDS

The geohydrological data of interest can be classified into the following categories: subsurface thermodynamic data (T,P), rock properties, fluid properties, fracture data, production data, and natural flow (mass and heat) data.

5.3.1 Thermodynamic Data

In order to determine the thermodynamic conditions at depth, static pressure and steady-state temperature data are required. Considerable temperature data from existing wells in the SSGF have been published by Younker et al (1982) and Elders and Cohen (1983). These data show that at a depth of 2 km the temperatures are typically over 320°C; the maximum temperature measured at SSGF is 365°C at 3.1 km depth. If these temperatures are extrapolated to the target depth of 5.5 km for a deep hole it is conceivable that a downhole temperature of ~500°C may be encountered. Thus there is a possibility of detecting regions of superconvection, if such phenomena actually exist. However, if a well is located on the flank of the main hydrothermal system, it is unlikely that such high temperatures will be encountered and actually probable that a temperature reversal with depth would be observed.

The hydrostatic pressure-versus-depth profile for the existing wells in the SSGF is almost constant at 0.098 bars/m (Helgeson, 1968), consistent with a constant fluid density of 1000 kg/m^3. The effects of increasing salinity with depth balances the effect of increasing temperature so that the fluid density remains constant with depth. Thus we may expect bottomhole pressures to be readily predicted for the proposed deep hole.

5.3.2 Rock Properties

The primary hydrologic rock properties of interest are permeability and porosity. In general, both of these parameters vary spatially, so that data on the variation in permeability and porosity with depth are desirable. Also, where the fluid flow is primarily through fractures, data on both fracture and matrix permeabilities and porosities are needed. Thus, single values of permeability and porosity cannot describe the hydrologic characteristics of the rock formation around the deep hole in sufficient detail. Data on porosity and permeability variations with depth are also extremely important for correlation with geophysical and geochemical data.

Data from existing wells in the SSGF indicate that horizontal intergranular (porous medium) porosities and permeabilities are relatively high in the shallower regions of the reservoir. Morse and Thorsen (1978) used well test data to calculate horizontal permeabilities of 100 - 500 md and Schroeder (1976) analyzed drill stem test data for the top reservoir and obtained a permeability of 500 md. Because of alteration the matrix porosity and permeability decreases with depth, but the overall permeability is enhanced by fractures at depth (Younker et al, 1982).

Also of considerable importance are the average well-to-well formation permeabilities and porosities. These data cannot be obtained if measurements are only made in one hole; simultaneous pressure measurements in other wells are needed. Knowledge of average permeabilities and porosities of a large volume of the reservoir rocks is important when estimates of the natural mass and heat flows within the reservoir are to be made, or reservoir response to exploitation is to be evaluated. Interference test data from the SSGF have been analyzed by Morse and Thorsen (1978). They calculate that the vertical permeability in the field is very low, presumably due to the low-permeability shale layers.

A physical property of less importance in assessing the hydrologic characteristics of the rocks is the rock compressibility. Information on this parameter can be obtained from laboratory core tests or hydraulic fracturing data.

The primary thermal property of importance is the thermal conductivity of the subsurface rocks. This parameter can also vary spatially, but depends primarily on the rock type and the porosity. Data on the variations in the rock thermal conductivity with depth are useful when the overall heat flow patterns in the geothermal system are being considered. Other parameters such as the densities and heat capacities of the rock matrix are less important, and can readily be obtained from laboratory measurements.

5.3.3 Fluid Properties

The fluids at SSGF are very saline; average total dissolved solids (TDS) are 280,000 ppm. Fluid properties such as density, viscosity, compressibility and expansivity are greatly dependent on salinity as well as temperature. As the fluid properties are very important when natural mass and heat flows in hydrothermal systems are considered, these properties must be determined. Fluid properties of pure sodium-chloride (NaCl) brines are available in the literature (e.g. Phillips et al, 1981) and these can be used as first estimates. If the chemical composition of the brines encountered in the SSSDP hole is sufficiently different from ideal NaCl mixtures, additional laboratory tests may be necessary.

5.3.4 Fracture Data

Although the subsurface rocks at SSGF consist of porous sedimentary units, there is substantial evidence that fractures contribute significantly to the reservoir permeabilities (Younker et al, 1982). This is especially true for deeper formations. At depths below 3 km, one would expect that fluid flow is controlled by the fractures. Thus, data on the fracture characteristics of the subsurface rocks are needed. Ideally, detailed statistical data on fracture distributions, apertures and lengths are required for a full understanding of the fracture system. However, for the deep hole, data on major fracture zones and their relative importance (permeabilities, etc.) would be useful. Also of interest is the variation in fracture frequency with depth and its correlation with permeability distribution with depth. Such data are extremely important when the economic potential of recovering geothermal brines from great depths is being considered.

5.3.5 Well Production Data

If the deep hole has sufficient permeability and temperature to sustain natural flow, a carefully designed production test (pit test) should be conducted. Data should be collected on the production characteristics (flow rates, enthalpies, chemical composition, etc.) of the well when flowing under different wellhead pressures. Furthermore, data on the changes in the flow characteristics of the well with time are useful. Also of interest are the depths at which the produced fluids enter the well. This will help to identify locations of major feed zones (fracture zones) and to determine if internal flow occurs in the well. Fluid samples should be taken at regular intervals and analyzed for the geochemical composition.

Also of great importance is the degree of damage (or enhancement) to the well due to the drilling operation (i.e., the skin value of the well). Proper tests should be conducted to determine the overall skin factor of the well as a function of flow rate.

5.3.6 Natural Flow (Mass and Heat) Data

Reliable estimates of the natural flow of mass and heat through the subsurface rocks in the vicinity of the proposed well are needed for various reasons. First, these data can help to determine the hydraulic and thermal interconnection between the deep hole and the main Salton Sea geothermal reservoir. Second, these data are important to establish geochemical and rock-fluid interaction models of the deep system. Third, these data can help determine the economic potential for deep geothermal resource development in the Imperial Valley.

Data on natural flow of mass and heat in geothermal reservoirs cannot be determined by direct measurements. However, such data can be obtained indirectly by integrating available knowledge into a model that can provide some reasonable estimates of the flows. Mass and heat transport in the SSGF has been studied by various investigators (Riney et al., 1978; Kasameyer et al., 1981; Younker et al., 1982). These authors conclude that large convection cells are not present. Instead, small-scale cellular convection is superimposed upon a large-scale lateral flow of pore fluid. This conclusion is supported by the near constant fluid density with depth (Helgeson, 1968). This and other hypotheses should be tested when data are available for the deep hole.

5.4 PROPOSED EXPERIMENTS FOR THE DEEP HOLE

In the last section some of the hydrologic data necessary for understanding the reservoir conditions in the vicinity of the deep hole were identified. In this section some of the tests needed to obtain these data will be discussed. It should be emphasized that many of these experiments cannot be carried out in a high temperature (>300°C) environment because the tools are temperature limited. However, these experiments are included as the downhole temperatures which will be encountered in the proposed deep hole are unknown.

5.4.1 In-situ Experiments

5.4.1.1 Temperature and Pressure Profiles

Temperature and pressure profiling in the well will provide the necessary temperature and pressure data with depth. These profiles should ideally be taken under steady-state conditions (i.e., when the well has fully heated up to ambient conditions). As will be discussed later, additional pressure-temperature surveys should also be taken during the heating-up period in order to identify permeability zones. Note, however, that if temperatures in the well are very high (>300°C), pressure profiling in the deeper portions of the well may not be possible.

5.4.1.2 Drill Stem Tests

During drilling, drill stem tests (DST) should be conducted at regular intervals. These tests can yield a sample of the reservoir fluid, indicate flow rates, yield an estimate of static and flowing bottomhole pressure and give short term pressure transient data. In the case of the proposed hole the DST should help determine reservoir conditions at depth and provide estimates of formation properties and wellbore damage.

5.4.1.3 Injection Tests

Determination of the permeability variation with depth in the deep hole is a difficult task. One expected problem arises because of the high temperatures (>300°C) anticipated in the deep hole, as the currently available instrumentation for such tests is temperature-limited. However, one possible method involves a series of injection tests using packers. These tests should initially be run with a single packer set at several levels, preferably below or above inferred conduits. Double packer tests should then be performed in zones containing the major conduits. Another advantage of using packers is that individual zones can be tested, so that data can be collected and analyzed to yield permeability variations with depth.

In order to conduct the injection tests, the formation must be sufficiently permeable to allow cooling of the wellbore. Both the packers and the pressure transducers are temperature-limited. However, if the injection tests are successful, valuable information on permeability variations with depth and fracture characteristics of the formation (double-porosity behavior) may be obtained. These data can be compared to various geophysical data obtained for the well (see Geophysics section). Pressure transient data from wells completed in high-temperature geothermal reservoirs have been successfully obtained from many fields, especially in Iceland and New Zealand (e.g., Grant, 1982; Bodvarsson et al., 1983).

5.4.1.4 Interference Tests

If nearby wells are available and time allows, interference tests should be conducted. During such tests pressure measurements are taken in one or more well(s) while production/injection takes place in another. These tests generally have to be of long duration since pressure responses at the observation wells are often not felt for weeks or months. However, if these tests are successful, average formation parameters (permeabilities and porosities) can be determined. These data can offer valuable insight into the hydraulic interconnection between the deep formations encountered in the borehole and the shallower reservoir regions.

5.4.1.5 Tracer Tests

Tracer tests usually also require the availability of nearby wells as these tests commonly involve injection of tracer in one or more wells, and observation of tracer returns in others. Tracer data can yield important information regarding the fracture characteristics of flow regime sampled by the tracer. Such data can be extremely useful in determining flow connections between wells, and in the case of the deep hole, the flow connection between shallow and deep reservoir zones.

5.4.1.6 Production Tests

The required production data can be obtained from a short-term pit test. During the test the wellhead pressure is varied in order to get data on changes in flow rates and enthalpies with changes in wellhead pressure. The test should be of long enough duration that flow rate and enthalpy variations with time can be recorded.

If well temperatures are not too high, a spinner survey should be conducted during the flow test so that the permeable zones feeding the well can be identified. If well temperatures are too high (>300°C) a spinner survey should be conducted during injection and the permeability zone accepting the injected fluids identified.

Also during the flow test, downhole samples of the reservoir fluids should be collected at various depths. The samples should be analyzed for the geochemical composition of the geothermal fluids and its variation with depth.

Immediately following the flow test, a build-up test should be conducted using a downhole pressure transducer. The pressure transient data from the build-up test should be analyzed to yield an average permeability of the formation adjacent to the well and the degree of damage (or enhancement) to the well (the skin factor). Radioactive tracer logs run under static conditions in the well may be useful in determining the locations and relative hydraulic potentials of conduits intercepting the well.

5.4.1.7 Fracture Data Analysis

Data on fracture zones can be inferred from such sources as:

- lost circulation zones during drilling;

- temperature/pressure profiles during heating-up;
- spinner surveys during production/injection;
- radioactive tracer logs.

Data from these different sources should be compiled and correlated and a general fracture-frequency vs. depth graph prepared. Additional information can also be obtained from the cores and the injection test data. Furthermore, if detailed data on fracture locations are desired, a televiewer log (which is temperature-limited) can be obtained during cold water injection.

Another possible experiment in the deep hole is a fracture propping experiment. If successful, this experiment would enhance the formation permeability through an artificial (man-made) fracture. Also the data from fracture propping experiments can help determine the in-situ stress conditions.

5.4.2 Laboratory Experiments

5.4.2.1 Rock Matrix Properties

Various hydrological and thermal tests on cores should be conducted in the laboratory using simulated in-situ conditions (temperature, pressure etc). The parameters of primary interest are:

- matrix permeability
- porosity
- thermal conductivity
- specific heat
- rock density.

The laboratory tests should attempt to obtain data from cores at various depths so that variations in these parameters with depth can be determined. This is especially important for parameters that can vary greatly with depth, such as permeability, porosity and thermal conductivity. Data on variations in the thermal properties with temperature is also useful.

5.4.2.2 Fluid Properties

As stated earlier, the Salton Sea brines are very saline (~280,000 ppm), so that pure water properties can neither be used in mass nor in heat transport calculations. It is possible that the chemical characteristics of the fluids are similar enough to pure NaCl mixtures so that known correlations for fluid properties of NaCl mixtures will be sufficiently accurate. If not, laboratory tests on the fluids from the deep hole should be undertaken in order to determine hydraulic and thermal parameters. The parameters of particular interest are:

- density
- viscosity
- specific heat
- thermal conductivity

The tests should be performed over appropriate ranges of temperature and salinity.

5.4.3 Modeling Studies

5.4.3.1 Natural Mass and Heat Transport

The natural flow of mass and heat in the subsurface rocks must be determined indirectly from various data from the deep well as well as other Salton Sea wells. The primary data required are downhole temperature and pressure profiles from the wells, and formation permeability values. These data are used in a model (analytical or numerical) to obtain estimates of natural mass and heat flows in the system. Other available data, such as geophysical and geochemical data, should be used as constraints on the model constructed.

5.4.3.2 Analysis of Temperature Transients

A series of temperature surveys is proposed during heating up of the well as well as during cooling from cold water injection. These data can be analyzed using analytical or numerical modeling techniques to infer variations in formation thermal conductivities with depth. Such modeling studies can also help identify feed zones and their relative importance. The calculated thermal conductivity values should be correlated with the thermal conductivity data from cores.

5.5 PRIORITY CONSIDERATIONS

The proposed geohydrologic experiments for the deep hole are listed in order of priority in Table 5.1. The experiments are divided into three categories, in-situ tests, laboratory test and modeling studies. A high priority item is the temperature and pressure surveys during heating-up and under steady-state conditions. These surveys are necessary for providing data that will determine the thermodynamic conditions at depth. However, if temperatures in the well become very high (400-500°C) these surveys cannot be made to bottomhole. The drill stem tests are useful as they can provide fluid samples during drilling and also provide data for approximate permeability determinations. If the well flows (sufficient temperature and permeability), production and buildup tests should be conducted. If temperatures again are

Table 5-1. Geohydrological tests listed in order of priority

1. In-Situ Tests

   a. Temperature and pressure surveys during heating under static conditions

   b. Drill-stem testing

   c. Production tests (if well flows)

   d. Build-up tests

   e. Inter-well tests (interference, tracer tests)

   f. Fluid samples/spinner surveys

   g. Injection tests (including temperature and spinner surveys)

   h. Fracture propping experiment

2. Laboratory Tests on Cores

   - rock matrix permeability
   - porosity
   - thermal conductivity
   - specific heat/rock density

3. Modeling Studies

   a. Model studies of mass and heat transport in the natural state

   b. Model studies of heating of the well

not excessive high temperature and high pressure fluid samples may be obtained. A spinner test would help identify fracture zones. A series of injection tests could provide data on permeability versus depth. However, these tests are only feasible if permeability is sufficient to allow cooling the wellbore. If not, it may be beneficial to attempt a hydrofrac experiment close to the bottom of the well in order to provide the necessary injectivity to cold water. During the injection tests, temperature and spinner surveys should be conducted.

The possible geohydrologic laboratory experiments on cores are not listed in order of priority as all of these should be performed. However, because of larger variations with depth, a greater number of core tests on permeability, porosity and thermal conductivity should be carried out than those determining specific heat or rock density. The modeling studies are necessary to determine natural mass and heat flows within the reservoir system encountered as well as to tie the information from the deep hole to conditions encountered in the main SSGF. Modeling of the heating of the well after drilling and/or injection should allow determination of thermal conductivity and diffusivity with depth.

6. ENGINEERING DEVELOPMENT REQUIREMENTS

6.1 INTRODUCTION

The majority of the drilling, completion, and logging technology which exists today was developed by the oil and gas industry for shallow (less than 2 km) wells of moderate temperatures (less than 100°C). The geothermal well which is planned as part of the Salton Sea project may be as much as 5 km deep with bottom-hole temperatures in excess of 400°C. For these reasons, many of the scientific experiments will not be possible using conventional technology, and special equipment, instrumentation, and measurement techniques will be required to meet the scientific objectives.

Even though plans may call for continuous coring for as much as 6,000 ft (1.8 km), provisions should be made to run as wide a suite of geophysical logs as possible. This is the case for three reasons. First, core recovery may be incomplete and thus the logs would provide the only quantitative information in those intervals. Second, logs provide information more rapidly than that which can be obtained from core analysis; and third, the combination of core and logs can greatly aid in the calibration of these logs.

The two areas most likely to prove operationally deficient in this high temperature environment are drilling (coring) technology and downhole instrumentation. The remainder of this discussion will deal with these two areas separately even though there is a great deal of overlap in the problems and solutions. It is important to note that it is unlikely that all of the problems will be foreseen. Since there is little historical perspective for the proposed operation, many of the situations encountered will be encountered for the first time and provisions for "on-site" technology development should be included in the planning. The following sections will also include an inventory of equipment and tools that are presently available -- both commercially and through the scientific community.

6.2 DRILLING TECHNOLOGY

This section, titled "Drilling Technology," is meant to address all areas of operation not included in the instrumentation discussion. Thus, it will include topics other than merely cutting the core.

Plans call for extending this well by coring for 1.8 km. The temperatures in this portion of the well are expected to vary from 300°C to 400°C. This formation will likely consist of dike swarms and metamorphosed argillaceous material, and cutting cores efficiently from this hard formation at elevated temperatures may require some new cutting technology. It is important to note that coring is infrequently done in oil and gas wells due to the increased drilling time, operational costs, and chances for sticking tools downhole. Thus, coring technology is not as well advanced as drilling technology (The Ocean Drilling Program extensively cores the holes which they drill, and their expertise should be included in any discussions of technology development in this area.).

Cores may be retrieved by one of two methods: "conventional" and wireline systems. Conventional coring involves the addition of a core barrel (10-30 m long) at the bottom of the drill string. When the core barrel is full, the entire string must be removed from the hole (termed a trip) in order to extract the desired core. The longer the core barrel, the more difficult it is to insure reliable downhole operation. If a 10 m core barrel is used to core for 2 km, then 200 round trips would be required to retrieve the core. Each round trip will require approximately 24 hours for a total trip time of 4800 hours. Rig costs may range from 200 to 300 $/hr. Thus tripping time to obtain core might cost at least $1M. These are not firm time or cost estimates, but are presented only to point out the advantage of a wireline coring system.

In a wireline coring system, the core barrel also is located above the bit, inside a special section of drill string. The advantage of this system is the capability to retrieve the core barrel with a wireline from the surface without tripping the drill string. The primary disadvantages of wireline systems are the small core size and the limited temperature capabilities. Technology development in this area would be very beneficial to the entire program. Table 6-1 is a list of some available coring system sizes which can be used for preliminary planning.

An additional factor to consider, regardless of which coring system is used, is the drilling fluid-core interaction. Some sort of drilling fluid must be used to cool and lubricate the bit and, if circulation can be maintained, to bring the cuttings to the surface for removal. If the core is permeable at all, then some of the fluid will penetrate the core and could confuse the scientific analyses of these cores. In many coring operations, special fluids are used to minimize this damage. These special coring fluids have not been qualified for high temperature use and thus some technology development will be required to realize this capability.

As noted in the chapter on Tectonics and Rock Mechanics, valuable information can be obtained by conducting hydraulic fracture experiments. Such experiments typically involve isolating an open hole section and then pumping fluid into this section until fractures are formed. An important piece of equipment required for this operation is the packer used in the zone isolation.

Table 6-1. Core Sizes*

Nomenclature	Core Diameter in/mm	Minimum Hole Diameter in/mm
Conventional (Longyear)		
RWG	0.74/18.7	1.18/29.8
EGW, EWM, EWL	0.85/21.5	1.49/37.7
AWG, AWM, AWL	1.19/30.1	1.89/48.0
BWG, BWM, BWL	1.66/42.0	2.36/60.0
NWG, NWM, NWL	2.16/54.7	2.98/75.7
HWG	3.00/76.2	3.91/99.2
2-3/4 x 3-7/8	2.69/68.3	3.88/98.4
4 x 5-1/2	3.97/101	5.50/140
6 x 7-3/4	5.97/152	7.75/197
Conventional (Christensen)		
	3.50/88.9	4.75/121
	4.13/105	5.75/146
	4.50/114	6.13/156
	4.75/121	6.25/159
	5.75/146	7.87/200
	6.25/159	7.87/200
	6.75/171	8.63/219
	8.00/203	9.63/245
Conventional Pressure Core (Heckes)		
	2.5/63.5	6.5/165
Wireline Coring (Longyear)		
AQ	1.06/27.0	1.89/48.0
BQ	1.43/36.5	2.36/60.0
NQ	1.88/47.6	2.98/75.7
HQ	2.50/63.5	3.78/96.0
PQ	3.35/85.0	4.83/123
Deep Hole, Wireline (Marshall)		
Super H Drill String	1.88/47.6	4.25/108
Super N Drill String	1.43/36.5	2.98/75.8

*"Drilling and Completions for the Continental Scientific Drilling Program," R. K. Traeger, Sandia National Laboratories.

These packers typically provide an elastomeric seal between the metal body and the borehole Extensive development of high temperature, open-hole packers has been done by the Los Alamos National Laboratory in support of the Hot Dry Rock Program, but this development has not been totally successful and further effort will be required if hardware is to be available for the Salton Sea well.

The above discussion highlights only a few of the specific drilling technology needs required for the scientific experiments. Since the scientific objectives will be met only if the hole is drilled, all the attendant drilling technology impacts the achievement of these goals. Examples of potential technology needs include: high temperature drilling fluids, lost circulation control techniques, corrosion resistant metals or corrosion control chemicals, high temperature explosives for back-off shots (to unstick drill pipe), high temperature cements, and efficient drill bits. In addition to these hardware items, analytic software to predict wellbore temperatures, fluid properties, and casing stress will be needed to define the environment and prevent other problems from occurring. Some of these technologies are being pursued -- both by the geothermal drilling operators and service companies and by the national labs as part of the DOE-sponsored Geothermal Technology Development Program. However, many of these are new, experimental technologies and should not be expected to perform with the same reliability as proven commercial hardware.

6.3 DOWNHOLE INSTRUMENTATION

As noted in the previous sections of this report, many of the proposed experiments involve the use of downhole electronic packages, both specialized experimental tools as well as standard industry devices in this particular well deserves some caution. Most of the geophysical logs (SP, gamma, resistivity) were designed for the oil industry (sands, shales, etc.) and are not calibrated for igneous or metamorphic rock. Secondly, these tools were designed for production holes and may be too large for the smaller core hole. Thirdly, they are typicaly rated for a maximum temperature of 175°C, well below the temperatures expected in the bottom part of this hole. Some of these conventional tools and their operational limits are noted in Table 6-2.

Specialized logging tools, many for scientific purposes, have been developed by several government agencies, including the USGS, Sandia National Laboratory, Los Alamos National Laboratory and the Lawrence Berkeley Laboratory. A list of some of these tools is contained in Tables 6-3 and 6-4. Many of these tools are experimental or one-of-a-kind and thus may not be widely available. Also, in most cases the agency responsible for development would likely insist that special operational consideration be given to the use of any of these tools.

Noting these lists of tools, it becomes apparent that no capability exists above 300°C. Since bottom-hole temperatures of 400°C are anticipated, an obvious gap in technology exists. Upgrading these tools to operate at higher temperatures is most certainly a worthwhile endeavor and should be vigorously pursued. However, the time required for this development may not be consistent with the schedule for the Salton Sea well, and thus other options must also be pursued.

One option that must certainly be considered is the cooling of the wellbore by pumping fluid down the drill pipe, returning up the annulus. This technique should be applied when possible, but there are at least two potential concerns. First, deep hot wells cannot be cooled a great deal by this method due to the heat-exhanger effect of the fluid circulating down the pipe and up the annulus. A temperature decrease of 50°C may be possible with this technique, but analytic methods (widely available) should be applied to

Table 6-2. Commercially Available Slim Hole Logging Tools*

Tool Type	Wellbore	O.D. (in)	Max. Press. (ksi)	Max. Temp. °F/°C
Schlumberger (Schlumberger Services Catalog, 1978)				
Resistivity				
Induction	Open	2-3/4, 3-7/8	20	350/175
Electrical	Open	3-3/8	25	500/260
Induction-Spherically Focused	Open	3-1/2	20	350/175
Dual Induction Laterolog	Open	3-3/8, 3/-7/8	20	350/175
Dual Laterolog	Open	3-5/8	20	350/175
Ultralong Spaced Electrical	Open	3-5/8	20	350/175
Porosity				
Formation density	Open	2-3/4	25	500/260
	Open	3-3/8	20	400/205
Compensated Sonic	Open	1-11/16	16.5	300/150
	Open	3-3/8, 3-5/8	20	350/175
	Open	2-3/4,3-3/8	25	500/260
Long Spaced Sonic	Open	3-5/8	20	350/175
Compensated Neutron	Open	2-3/4	25	500/260
Natural Gamma	Open	3-5/8	20	350/175
Temperature				
Temperature	Open	1-11/16	15	350/175
Flowmeter-Temperature	Open	1-11/16	20	500/260
Drill String				
Electrical	Through	1-1/2	20	350-500/175-200
Induction	Drill Stem	2-3/4	20	350-400/175-205
Sonic	Drill Stem	1-11/16	16	300/150
Neutron	Drill Stem	2-3/4	25	500/260
Formation Density	Drill Stem	2-3/4	25	500/260
Gamma Ray	Drill Stem	2-3/4	25	500/260
Gamma-Neutron	Drill Stem	2-5/8	25	500/260
Thermal Decay	Drill Stem	1-11/16	16.5	300/150
Production Logging				
Continuous Flowmeter	Cased	1-11/16	15	350-600/175-315
Gradiometer	Cased	1-11/16	15	350/175
High Resolution Thermometer	Cased	1-11/16	15	350/175
Fluid Sampler (650 & 836 cc)	Cased	1-11/16, 2-1/2	10	350/175
Radioactive Tracer	Cased	1-11/16	20	275/135

*Slimhole Instrumentation, R. K. Traeger, Sandia National Laboratories

Table 6-2. (continued)

Tool Type	Wellbore	O.D. (in)	Max. Press. (ksi)	Max. Temp. °F/°C
Logging in Casing				
Gamma Ray	Cased	1-11/16, 2, 2-3/8,3-3/8	20	350-500/175-260
Neuron	Cased	1-11/16, 2, 2-3/8,3-3/8	12-25	350-500/175-260
Thermal Neutron Decay	Cased	1-11/16	16.5	300/150
Dresser Atlas				
Electrical				
Induction-Electrolog	Open	2.0	17	350/175
Dual Induction Focused	Open	3-5/8	18	350/175
		3-3/8	25	400/204
Dual Laterlog	Open	3-5/8	20	400/204
Radioactive				
Compensated Neutron	Open	2-3/4, 3-5/8	20	300/150
Gamma-Neutron	Open	1-11/16, 3-3/8 2-3/4, 3-3/8	17	300/150
Compensated Densilog	Open	3	20	300/150
Epithermal Neuteron	Open	3	20	300/150
Gamma Spectra	Open	3-5/8	20	400/204
Acoustic				
Acoustilog	Open	2-3/4	20	450/
		3-3/8, 3-7/8	20	350/175
Production Logging				
Nuclear Flolog	Cased	1-1/2	12	350/175
Tracerlog	Cased	1-1/2	12	350/175
Fluid Density	Open or Cased	1-3/4	15	400/204
Temperature	Open or Cased	1-1/2, 1-11/16	18	325/163
		1-11/16	17	400/204
Flowmeter	Open or Cased	1-11/16, 1-1/8	18	300/150
Fluid Sampler	Open	1-11/16	10	300/150

Table 6-3. USGS Logging Tools, January 1982*

Temperature Range	Log Type	Required Hole Diameter
100°C	sonic ratio (far/near) sonic delta-t sonic waveforms sonic velocity sonic amplitude	4-1/2" hole; 3" if smooth hole
300°C	8" resis., normal, uncomp. 16" " " " 32" " " " 64" " " " 8" resis., normal, comp. 32" " " " 64" " " " 8" wenner resis., uncomp. 16" " " " 8" wenner IP 16" wenner IP 10 cm Dakhnov IP 40 cm Dakhnov IP	3" 3"
!00°C	compensated dual density density computer from near detector density computed from far detector near detector count rate far detector count rate caliper form density probe	4-1/2"; 3" if smooth
300°C	3-arm caliper	3"
100°C	neutron count rate neutron porosity neutron API units gamma ray count rate gamma ray API units equivalent U from gamma ray	3" 3"
80°C	magnetic susceptibility (volts) magnetic susceptibility (micro CGS) magnetic susceptibility (micro SIO)	4-1/2"; 3" if smooth

*USGS Branch of Petrophyhsics and Remote Sensing

Table 6-3. (continued)

Temperature Range	Log Type	Required Hole Diameter
	self potential (single point)	
	self potential (8" differential)	3"
	self potential (16" differential)	
300°C	single point resistance	
	8" differential resistance	3"
	16" differential resistance	
	temperature	
100°C	vertical component magnetometer	3"
	directional survey	

Table 6-4. DOE Logging Tools

Temperature	275°C	Los Alamos National Lab.
Temperature	275°C	Sandia National Lab.
Temperature	1000°C	Sandia National Lab.
Caliper	275°C	Los Alamos National Lab.
Fluid Velocity	275°C	Los Alamos National Lab.
Fluid Velocity	275°C	Sandia National Lab.
Fluid Velocity	275°C	Lawrence Berkeley Lab.
Gamma	275°C	Los Alamos National Lab.
Geophone	275°C	Los Alamos National Lab.
Accelerometer Acoustic	275°C	Los Alamos National Lab.
Acoustic Detonator	275°C	Los Alamos National Lab.
Borehole fluid Sampler	300°C	Lawrence Berkeley Lab.
Borehole Televiewer	275°C	Sandia National Lab.
In-Situ Periodic Source	300°C	Sandia National Lab.

the specific well conditions to better quantify this condition. A second option, open only if there is a highly permeable zone in the well, is to pump down the annulus (or drill pipe) and into the fractured zone. This technique can lead to wellbore temperature 100° to 150°C below the formation temperature if the flow rates can be maintained at sufficiently high levels.

Both of these methods assume that the borehole cooling does not affect the particular measurement being made. This may be the case, but care should be given to assess this effect on the calibration of any tools. (Some formation properties are temperature dependent and the temperature may not be accurately known.)

If the hole size is sufficiently large (cored holes are typically quite small) some increased temperature capability may be realized by encasing the tool in a Dewar, and/or using some phase change material to absorb the heat. For this method to be effective, the downhole time must be limited to a duration such that the instrument will not exceed its rated operating temperature. Depending on the phase change material, configuration and size of the Dewar, this time period will vary from a few hours to a day. This technique is additionally limited because many sensors must be exposed to the downhole enviornment in order to make the necessary measurement. The Los Alamos Lab has conducted extensive development in this area.

In addition to the tools, the cable and cablehead (connector from tool to cable) have inherent temperature limitations. These limitations derive from the use of elastomeric materials used as seals and insulators. Both Sandia and Los Alamos National Labs have done extensive development in this area, and there are now cableheads which can operate in the 250° to 300°C range. However, further development may be required since these cableheads must be designed to interface with each downhole tool. Conducting wireline systems may prove to be the limiting factor in the deep, hot portion of the well. Single conductor, high temperature (300°C) cables are available from a few commercial service companies. Los Alamos National Labs has two high temperature wireline units with seven conductor cables capable of 250°-300°C operation, but no commercial version of this type is known to be available.

6.4 CONCLUSIONS

The opportunity to collect data from a deep, hot borehole is an exciting one, and every effort should be made to insure that the state-of-the-art in engineering technology is brought to bear to achieve this goal. These engineering capabilities may be divided into three basic temperature ranges: 20° to 150°C, 150°C to 300°C, 300°C and greater. In the low temperature range, there is a great deal of commercially available technology and most scientific experiments should not be limited by the availability of equipment. In the range of 150°C to 300°C there is limited commercially available technology and limited "laboratory" available technology. Experiments to be conducted in this regime will undoubtedly be limited by the temperatures, but with proper technology development and innovative use of existing equipment some portion of the experiments is possible. There is almost no capability above 300°C, and solutions in this temperature range will require long-range (2 to 4 years) technology development programs. Experiments and instrumentation development should be carefully coordinated to avoid unnecesary duplication of efforts and the expense of redundant equipment purchase. At the very least an attempt to standardize cableheads and seals, and the purchase and shared use of a high temperature cable, should be pursued. If future deep hole programs are planned which involve experiments at temperatures above 300°C, then engineering technology programs to meet these scientific needs should be started now, in order to be available in the future.

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