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**Case History Report on
East Mesa and Cerro Prieto Geothermal Fields**

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

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Case History Report on East Mesa and Cerro Prieto Geothermal Fields

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Page

CONTENTS

ABSTRACT	1
1. INTRODUCTION AND BACKGROUND	3
1.1 STATUS OF GEOTHERMAL WELL LOGGING	3
1.2 THE NEED FOR CASE HISTORIES	5
1.3 THE IMPORTANCE OF EAST MESA AND CERRO PRIETO	7
2. FIELD DESCRIPTIONS	8
2.1 EAST MESA	8
2.2 CERRO PRIETO	12
3. TASK 1: COLLECTION OF EXISTING DATA	12
4. TASK 2: INTERPRETATION OF GEOPHYSICAL WELL LOGS	16
4.1 QUALITY OF LOG AND CORE DATA	17
4.2 GENERAL OBSERVATION ABOUT LOG RESPONSES	21
4.3 ASSESSMENT OF INTERPRETED DATA	25
4.4 SPECIAL PROBLEMS - TEMPERATURE EFFECTS	51
5. TASK 3: EVALUATION OF LOG INTERPRETATION	78
5.1 USEFULNESS OF INTERPRETATIONS	78
5.2 CORRELATION OF LOG INTERPRETATION WITH OTHER RESERVOIR INFORMATION	90
6. CONCLUSIONS	102

APPENDIX A:	WELL LOG LIST - EAST MESA	105
APPENDIX B:	WELL LOG LIST - CERRO PRIETO	119
APPENDIX C:	TABULAR DATA - EAST MESA	155
APPENDIX D:	COMPUTER LISTINGS OF TEMPERATURE PROFILE AND HEAT FLOW CALCULATIONS	165
REFERENCES AND PARTIAL BIBLIOGRAPHY		171

CASE HISTORY REPORT ON EAST MESA AND CERRO PRIETO
GEOTHERMAL FIELDS

by

D. G. Davis and S. K. Sanyal

ABSTRACT

The geothermal resource has become an increasingly important alternate energy source in recent years. This has led to increased emphasis on developing and refining the technology involved in the development and production of geothermal energy.

Well log analysis as applied to the geothermal industry is one of the areas of technology in great need of further development. One means of improving log analysis technology is to study case histories of the past uses of log analysis as applied to specific fields.

The project described in this report involved case history studies on two well-known geothermal areas in North America: The East Mesa field in California and the Cerro Prieto field in Mexico. Since there was considerably more pertinent material available on East Mesa, a major part of the effort on this project was devoted to studying the East Mesa field.

One particular problem that first came to attention when studying the Cerro Prieto data was the difficulty in determining actual formation temperature at the time of logging. Since the temperature can have a significant effect on well log readings, an accurate temperature determination was considered to be important. This problem concerns all geothermal well logging so considerable effort was devoted to it in this study.

1. INTRODUCTION AND BACKGROUND

1.1 Status of Geothermal Well Logging

The geothermal resource is an important alternative to fossil fuels in the western United States. In recent years, a massive effort has been launched by private industry, federal, state, and local governments, and some research organizations to explore, assess, and develop domestic geothermal resources. However, this effort has been seriously impeded by many deficiencies in technology, particularly in the area of well logging.

A geothermal resource is explored from the surface by various techniques: geological, geophysical, geochemical, etc. However, the resource can be proved only by drilling into the geothermal reservoir. A well log is essentially a vertical profile of a particular rock property as measured in the well after it has been drilled. Common well logs measure such rock properties as electrical resistivity, acoustical velocity, and natural radioactivity. The rock logged may or may not be fluid-saturated. The "depth of investigation" of common well logs varies from a few centimeters to several meters radially outward from the borehole. While the "reach" of a well log in the areal sense is far less than that of a surface geophysical survey, well logs can provide physical properties averaged over a short vertical distance and therefore provide a far more detailed delineation of the reservoir characteristics. Also, by correlating logs from several wells, one can gain insight into the areal distribution of the reservoir properties. For these reasons, interpretation of well logs is an important step in the assessment of reservoir characteristics, which determine the development potential of the resource. During exploration, an interpretation of existing well logs can provide valuable data to supplement surface geophysical surveys. During

development of a geothermal field, the well logs may indicate which parts of the reservoir have the most favorable commercial potential, and in which sections a well should be completed. In forecasting reservoir performance and in production planning, well log interpretations can provide the basis on which a mathematical model of the reservoir is developed to aid in reservoir studies. Well logs can be used to monitor reservoir production, subsurface movement of waste water, and various other legal and environmental aspects of the geothermal resource development. Thus, in all phases of geothermal resource development, well logs are extremely useful.

In the petroleum industry, well logging is a well-developed discipline that has matured over a fifty-year period. Compared to this, geothermal well logging is a very new field of activity. Current practice has largely been to use the same logging equipment and the same log interpretation techniques for geothermal wells as is commonly used for petroleum wells. However, this approach has often proved to be inadequate in many geothermal areas. The problems have generally been of two types: (1) those associated with logging equipment, and (2) those connected with log interpretation techniques. Temperatures encountered in geothermal wells are normally higher (greater than 175°C or 350°F) than those found in petroleum wells. In many geothermal wells, some of the standard well logs cannot be run because the well temperatures are higher than the maximum temperature for which the logging tools are designed. Lack of financial incentive has so far discouraged major efforts by logging service companies to improve logging instrumentation or interpretation techniques for geothermal wells. Baker, et al. (1975) and Sanyal, et al. (1977) provide discussions of the state-of-the-art of geothermal well log analysis and point out some of the problems. (A reference list and partial bibliography can be found at the end of this report.)

Recognizing these problems, the US Department of Energy (DOE) initiated in 1976 a substantial research program for development of improved well logging tools for geothermal wells. The manager of this program, Sandia Laboratories, has already developed new tools or improved upon some old ones. The tools and components developed under the program will be available to the geothermal industry in due course. In 1977, DOE initiated a research program in geothermal well log interpretation with the Los Alamos Scientific Laboratory as the manager. The project discussed in this report developed as a part of the DOE geothermal log interpretation program. The objective of the present project is to provide case histories of geothermal well log interpretation and the application of these interpretations in the development of a geothermal resource.

1.2 The Need for Case Histories

It is apparent that a number of technical problems, both in logging equipment and log interpretation techniques, have to be solved before geothermal well log interpretation reaches the reliability of its counterpart in the petroleum industry. However, during the last two decades, many well logs have been run in geothermal wells in the United States and other countries and experience is being gained in the industry.

Some geothermal fields have been producing energy for several years. For example, the Larderello field in Italy, Otake field in Japan, Matsukawa field in Japan, Wairakei field in New Zealand, Cerro Prieto field in Mexico, Ahuachapan field in El Salvador, and The Geysers field in northern California have been producing geothermal energy for several years. Ideally, in the fields where well logs are available, if one compared the predicted performance based on the interpretation of the logs to the actual performance under geothermal production, a great deal could be learned

about the effectiveness, the strong points, and the weak links in the interpretation of geothermal well logs. Publication of such case histories has proved invaluable in many industries; for example, oil and gas industry literature is replete with case histories of reservoir development and well log interpretation. However, in the geothermal industry very few published case histories of geothermal log interpretation and its application are available. The reasons for the lack of published case histories are several: (1) Temperature limitations of logging equipment and consequent scarcity of data from very hot wells; (2) Confidentiality of information on the part of well operators, largely due to leases, operating agreements and development plans not being finalized; (3) Unreliable or ambiguous results that have been obtained from many geothermal well logs because of the lack of proper interpretation techniques, or because of the unresolved effects of unfamiliar lithologies or high temperatures.

It would be desirable to have a number of case histories where geothermal well log interpretation was of substantial value in unraveling the resource characteristics. Such positive case histories would help in establishing the state-of-the-art of geothermal well logging, and help to develop confidence in well log analysis in this relatively immature industry. However, even negative case histories, such as cases where well log analysis did not contribute to the resource assessment, are of value because they can point out the specific needs for development or improvement of interpretation techniques or logging equipment. Compilation and judicious analysis of such case histories, both positive and negative, should help lower the risks involved in geothermal energy development by reducing the uncertainty in the estimation of geothermal reserves and production capacities.

As has been pointed out before, well log interpretation is an important activity in all phases of the geothermal

industry such as exploration, assessment, drilling, development planning, production monitoring, and also in satisfying many environmental and legal requirements. Successful completion of DOE's Case Histories Program should aid in deriving the maximum amount of information from currently used log suites, thus increasing the benefit-to-cost ratio, the dissemination of the state-of-the-art, and the standardization of log interpretation and applications. Improved interpretation and careful use of well logs may avert costly failures or inefficient operations in some geothermal fields. The potential direct beneficiaries of this program include private geothermal resource developers, companies that provide well logging services, government agencies, and the scientific and industrial community in general.

1.3 The Importance of the East Mesa and Cerro Prieto Fields

This project considered the histories of two well known geothermal fields: East Mesa in the Imperial Valley of Southern California and Cerro Prieto in the Mexicali Valley of Mexico. The reasons for choosing the East Mesa and Cerro Prieto fields are several. In the United States, the only commercially producing geothermal reservoir is The Geysers. Unfortunately, the availability of well logs from The Geysers field is limited. Because of the high temperature, abnormal reservoir pressure, and unusual fluid (steam) in the borehole, it has been impossible to obtain complete suites of well logs in this field. Those logs that have been run at The Geysers are not generally released to the public.

The only other geothermal area in the United States where well logging is established and production of the geothermal resource on a limited scale has taken place is the Imperial Valley. Of the Imperial Valley reservoirs, the logs from the Heber and the Brawley fields are proprietary and unavailable. Those well logs from the Salton Sea

field that are available are old and of very poor quality. The new well logs from the Salton Sea are of a proprietary nature. East Mesa is the only geothermal reservoir in the Imperial Valley that has undergone considerable development for a significantly long period and that has publicly available well logs and reservoir data.

One reason for including Cerro Prieto in the study is that, although the Cerro Prieto and the East Mesa reservoirs are geographically close and genetically of the same type, in the Cerro Prieto reservoir the temperatures are much higher (300°C and greater, as compared to 150°C for East Mesa). Moreover, in the Cerro Prieto geothermal field, there is considerably more hydrothermal alteration of rocks than in the East Mesa field. Also, the Cerro Prieto geothermal reservoir has been producing for five years, and more production data and reservoir performance information have been collected. Lastly, a large number of well logs and related well data have been accumulated for the Cerro Prieto reservoir. (However, not all of the data was as readily available as had been anticipated.) Considering the fact that in the next decade Cerro Prieto is expected to produce about 400 megawatts of power and the Imperial Valley is expected to produce well over 1000 megawatts, the importance of studying East Mesa and Cerro Prieto becomes obvious.

2. FIELD DESCRIPTIONS

2.1 East Mesa

The East Mesa KGRA (Known Geothermal Resource Area) is one of several geothermal fields in the Imperial Valley in southern California. It is located on the east side of the valley, approximately 11 km (7 miles) southeast of Holtville and 117 km (110 miles) east of the San Diego metropolitan

area as shown in Fig. 2.1. East Mesa has been the site of much geothermal exploration and development. Part of the field has been developed by the United States Bureau of Reclamation (USBR), which drilled five wells (Mesa 6-1, 6-2, 8-1, 5-1, and 31-1). North of the Bureau of Reclamation development, Republic Geothermal, Inc. has drilled seven wells [18-28, 16-29, 16-30, 38-30, 56-30, 78-30, and 52-29 (injection well)] and to the south, Magma Energy Company has drilled three wells [44-7, 48-7, and 46-7 (injection well)]. All of these wells are currently available for production or injection of fluids. There are four old abandoned wells on the outskirts of the area (Texaco Grupe-Ingebretsen No. 1, Magma Sharp No. 1, Shafer Barbara No. 1, and American Petrofina USA No. 27-1). Figure 2.2 shows the well locations as of 1976. In addition to these wells, there are many shallow wells in the area used for fresh water production.

Republic Geothermal has recently announced plans for a 48-megawatt power plant to be constructed in East Mesa. The first phase of the construction is scheduled for completion in late 1979 or early 1980 with the main plant to be completed in late 1980.

The East Mesa KGRA is on the east flank of the Salton structural trough. Wildcat wells in the area indicate that deltaic sediments reach a depth greater than 3200 m and bedrock is probably as deep as 3700 m (Bureau of Reclamation 1974). Layers of water-saturated, poorly consolidated sand and silt of the Colorado River delta and coarse detritus of local marginal origin have been collecting on the granitic basement since the earliest Pliocene time (Nichols and Hollenbaugh 1975). These Colorado River delta sediments are predominantly quartz and calcite, with some dolomite, plagioclase, potassium feldspar, mica and clay; gypsum occurs sporadically throughout the sediments (Muffler and Doe 1968). The body of literature on geological/geophysical/geochemical studies in the Imperial Valley is very large.

Fig. 2.1. East Mesa Area Location
(from TRW Systems Group 1976a).

Fig. 2.2. Well locations as of 1976.

2.2 Cerro Prieto

The Cerro Prieto Geothermal Field is located on the western margin of the Salton Trough, 35 km south of Mexicali in Baja California as shown in Fig. 2.3. Initial exploration by the Comision Federal de Electricidad began in 1959 and development of the field resulted in a 75-megawatt generating plant being placed on line in 1973. Steam flashing from 18 wells provides the geothermal energy for the power plant operation. By 1981, an additional 105-MW facility will be added to the existing facilities. Another power plant will be producing 55 MW by 1983, and an additional 165 MW is to be added by 1985 for a grand total of 400 MW. Figure 2.4 shows details of well and plant locations.

Production of hot brine (maximum formation temperature encountered is 347°C) is from two main sand/shale reservoirs, which compose part of the Colorado River delta. The reservoirs are complicated by two fault systems, the principal one a predominately NW-SE strike and a smaller fault system being oriented with a SW-NE strike.

Well completions are extremely difficult under the hostile environment caused by high temperatures and fluid corrositivity. Early wells had some problems of casing collapse and fracture but with experience and engineering improvements, this type of problem has been greatly reduced. Studies have shown that wells that are completed in more than one producing interval increase the possibilities of incrustation. Improvements are needed in the areas of high-temperature cementing and corrosion control in order to solve other mechanical problems.

3. COLLECTION OF EXISTING DATA

This case history study was initiated with the collection of publicly available well logs, log interpretation

SALTON TROUGH MAP SHOWING IMPERIAL and MEXICALI VALLEYS

(From Palmer et al. 1975)

Fig. 2.3

CERRO PRIETO GEOTHERMAL FIELD WELL LOCATIONS (As of March 1978)
(From Witherspoon et al. 1978)

Fig. 2.4

reports, and reservoir information from the fields under study. Ideally, the data base should consist of:

- Copies of well logs - analog traces or computer tapes
- Processed well logs - computer printouts or traces
- Log interpretation reports
- Geological/Geophysical/Geochemical data
- Core analysis information
- Well test data
- Production history

Such data were to be collected, sorted, checked and modified where necessary.

The primary sources of data for East Mesa were the US Bureau of Reclamation, Boulder City, Nevada and the Republic Geothermal Company of Santa Fe Springs, California. For Cerro Prieto, the source was the data bank on Cerro Prieto maintained at the Lawrence Berkeley Laboratory of the University of California. Appendix A and Appendix B list all the well logs collected from East Mesa and Cerro Prieto, respectively. Appendix C contains tabular data pertaining to the East Mesa wells. Because of the large volume involved, this report does not include reproductions of well logs or other raw data. Portions of processed or interpreted data are reproduced, where necessary, to illustrate points under discussion in the report.

The data gathering part of this study took much longer than had been anticipated. Although much of the data were easily available, some key data, such as interpreted dipmeter logs from East Mesa, were difficult to acquire. Most of the reproduced logs from East Mesa were purchased from Petroleum Information, Incorporated. Of the interpretive reports, the most comprehensive treatment of East Mesa is contained in the reports by the TRW Systems Group of Redondo Beach, California, with INTERCOMP Resource Development and Engineering, Inc. of Houston, Texas as subcontractor.

The first of these reports (TRW Systems Group 1976a) was prepared for the Bureau of Reclamation and the second, (TRW Systems Group 1976b) was prepared for the US Energy Research and Development Administration. At the end of this report, a list is provided of relevant publications about East Mesa and Cerro Prieto.

The data from Cerro Prieto was not nearly as complete as had been anticipated, or as complete as would have been desirable. Most of what was available was obtained from the Lawrence Berkeley Laboratory, but the amount of data available is relatively scarce when compared to that available on East Mesa. Most of the interpretive log data available on Cerro Prieto consist only of computer processed logs (SARABAND*) from Schlumberger Well Services. The lack of detailed interpretive data was a serious handicap in making a comprehensive case history study of this field, since it was not within the scope of this report to make new log interpretations. For this reason, more effort on the study was spent on the East Mesa field than on Cerro Prieto.

4. INTERPRETATION OF GEOPHYSICAL WELL LOGS

The case history study assumed that the basic interpretations of the well logs had been performed by the operators of the East Mesa and Cerro Prieto fields. This task did not require reinterpretation of those logs. Instead, the objective was to perform a critical evaluation of the previous interpretations in order to improve them where possible, fill in the interpretation if required, and compare the reservoir information gained from the well log interpretation with that obtained from other geotechnical data and

* A Schlumberger trademark.

production of the reservoir. The main thrust of this section was to assess the quality of the existing data and interpretations from these fields.

4.1 Quality of Log and Core Data

The quality of logs from East Mesa is variable but generally better than had been expected. The logs from wells drilled in the 1960's are of earlier vintage and logging suites are incomplete. The logs on wells drilled since the mid 70's are more modern and of better quality. The rather moderate temperature (150°C) of East Mesa has allowed reasonably successful logging operations with conventional logging tools, and without the need for massive cooling of the well bores before logging. Few serious problems in repeatability, scale, sensitivity, or depth relations have been observed on the logs from East Mesa wells drilled during the past few years.

The time constant of all radioactive logs run in East Mesa is 2 s, and these logs were run at speeds of 0.15 to 0.20 m/s, giving a log or data averaging interval of 0.3 to 0.4 m, which is acceptable. There are some examples of poor log quality such as: (1) Density log porosities in East Mesa 18-28 read too high due to miscalibration, (2) The first run of the Compensated Neutron Log in Mesa 38-30 was considered unreliable in the TRW Systems Group (1976a) study, and (3) In some wells, mud cake build-up reduced the quality of some logs.

It also should be noted that the occurrence of fresh formation water, such as in the Republic Geothermal wells, complicates the use of the spontaneous potential curve (SP) recorded on electrical logs for quantitative calculations of salinity. This is due to the prevalence of unknown quantities of multivalent ions, such as Mg, Ca, and SO_4 . The multivalent ions may have chemical activities

quite different from pure NaCl solutions whose effects are well known (Schlumberger 1972).

Geothermal wells are cooled significantly by mud circulation (as in East Mesa) or by icing down the mud (as in Cerro Prieto) before logging. Initially, this cooling effect in the wellbore and the surrounding area was thought to significantly affect the response of the induction log. This relationship was studied in detail in this project because of its possible serious effect on all geothermal well log analysis. The results of these investigations are covered in detail in Section 4.4.

It should be pointed out that temperature changes may affect rock properties, such as the acoustic velocity of the matrix. For example, Timur (1976) reported an average decrease of 1.7% in compressional wave velocity and 0.97% in shear wave velocity for a 100°C rise in rock temperature. Hence, acoustic log response in geothermal wells may be affected slightly by the temperature changes, with travel time decreasing with temperature. Acoustic logs are often of poor quality in shallow sedimentary sequences because of incomplete compaction of sediments, and a compaction correction to the acoustic log response is normally required for sand/shale sedimentary sequences at depths shallower than about 1500 m. The geothermal reservoir in East Mesa lies between the depths of 900 to 1850 m, and compaction corrections are required for the acoustic logs run in these wells. Calculations of compaction correction factors from the East Mesa well logs showed this to be true.

For a clean sandstone lithology, the density log is usually the most reliable porosity device. This was found to be true for East Mesa, except when one or more of three conditions occur: (1) Hole washouts and/or rugosity perturb the density readings and cause unpredictably high porosity values; (2) Shaliness requires more complex interpretation techniques for the determination of effective porosity;

and (3) Excessive mud cake thickness may cause erroneous density readings.

Neutron logs in East Mesa are useful. In combination with density logs, they can be used to distinguish shale-free, water-saturated zones from shaly water-saturated zones or shale-free gas bearing zones. This discrimination has been possible in most East Mesa wells because combination density-neutron logs have been run in most of these wells. This point is discussed in the next subsection.

Gamma ray, spontaneous potential, and caliper logs in the East Mesa wells generally have normal response and quality. However, in enlarged borehole sections, gamma ray responses need significant correction. Also, base line drifts on SP logs are present in many wells. Temperature and dipmeter logs appear to be of normal, acceptable quality.

Unlike conditions at East Mesa where formation temperatures are not an extremely serious problem in logging operations, the static formation temperature at Cerro Prieto is well above the temperature rating of most logging tools. Logging operations must be commenced as quickly as possible following completion of drilling and circulation. Advantage can be taken of a mud circulation system incorporating cooling towers. In addition, the mud may be further cooled with ice.

Normally, in Cerro Prieto, a continuous temperature log is run first to establish the temperature environment that will be encountered by other logs. Three maximum reading thermometers are run with each log, and agreement between these three readings is usually within two or three degrees. By maintaining an accurate time and temperature profile, reasonable estimates can be made as to the time when the borehole environment will surpass tool limitations. If necessary, the borehole will be cooled again with additional mud circulation before continuing the logging operation.

Considering the hostile conditions encountered when logging the hot wells at Cerro Prieto, the success of the logging operations and the quality of the logs is quite good.

Core analysis data were not available from all wells in East Mesa. Most of the cores taken were of the sidewall type which, in unconsolidated or semi-consolidated sediments such as are present in East Mesa, do not yield reliable measurements of porosity and permeability values. The problems in the analysis of sidewall cores are caused primarily by two conditions: (1) Disturbance of the in situ stress conditions and pore geometry in the core recovery process; and (2) Possible drying of some clays before measurements are made. Also, it is now generally accepted that temperature affects rock properties, particularly permeability. (Sanyal et al. 1974). An increase in temperature reduces effective permeability. Although the core analysis procedure was not described in the available reports, the measurements were assumed to have been carried out at room temperature. Thus, the measured core permeabilities may be too high. Also, it is not known under what effective overburden pressure the permeability measurements were made. Since higher overburden pressure reduces permeability, the core permeabilities measured at surface pressure are likely to be too optimistic. Usually, permeabilities reported in core analysis reports are measured for gas flow. The permeability of a core, as measured with water flow, is often lower than its permeability to gas because of the swelling of some clay minerals upon contact with water. Permeability to water, particularly brine, may be as much as an order of magnitude lower than the permeability to gas. It is quite likely that all these factors have resulted in the reported core permeabilities being too high. The porosities, however, are less likely to be significantly in error because most of the factors discussed above do not greatly affect porosity.

4.2 General Observations about Log Responses

A qualitative checking of all well logs in East Mesa and Cerro Prieto revealed a number of features that are characteristic of these fields. These features, most of which are also seen in similar sedimentary sequences in petroleum wells, include the following:

1. In East Mesa, SP logs show base line shifts indicating different formation water composition and/or salinities at different depths.

The large contrast between mud filtrate and formation water salinities in Cerro Prieto results in well defined SP characteristics. Base line shifts do occur but are easily defined. The SP is commonly used for correlation and as one of the clay indicators in SARABAND computations.

2. Gamma ray intensity and hole size (from the Caliper log) seem to correlate in many East Mesa wells, indicating that enlarged hole sections are usually the shalier ones.

Excessive hole washout is not usually a problem in Cerro Prieto. The gamma ray responds much in the classical manner in the sand and shale series. The gamma ray is used as a clay indicator in SARABAND computations.

3. In both the East Mesa and Cerro Prieto fields the commonly used mud type is fresh water/chemical gel, and the water loss characteristics of the mud in both areas are normally maintained within petroleum industry standards. The resistivity profiles between the shallow and deep reading resistivity devices recorded on East Mesa wells vary with depth, sometimes indicating an increase and sometimes a decrease in the diameter of invasions with well depth. However, the profile is also affected

by the contrast between mud filtrate and formation water resistivities. With changing formation water salinities, observations concerning invasion diameters must be influenced by a consideration of fluid resistivities.

4. For a clean water-bearing sand, the density and neutron porosities should be equal if the sand is shale-free. In most zones in East Mesa, the neutron porosity is higher than the density porosity, indicating that the lithology is primarily shaly sand. The upper and lower parts of Fig. 4.1 show examples of such zones from East Mesa 18-28.

In Cerro Prieto, the density and neutron log responses are normal for a sand/shale sequence.

5. In some rare zones in East Mesa wells, the neutron porosity is lower than the density porosity, possibly indicating the presence of gas. Geothermal water is known to contain a variety of dissolved gases, such as CO_2 , H_2S , NH_4 , and CH_4 . However, only rarely is free gas saturation encountered in a virgin geothermal formation. Some free CO_2 -bearing zones have been reported from Cerro Prieto. It may be possible that such zones exist in the East Mesa wells, but have remained undetected--being first masked by mud filtrate invasion, then by the casing. Figure 4.1 shows a possible example from East Mesa. Notice that on this section of log, gas appears to occur in the upper part of the sand. It is tempting to explain this as being due to gravity segregation of gas as is common in oil or gas wells. It must be pointed out that, after the neutron porosity readings are corrected for temperature and other effects, the neutron porosities are not as low as indicated on the log. Even

Fig. 4.1

CNL/FDC LOG - EAST MESA 18-28

after correction however, the neutron porosities are still somewhat lower than the density porosities, and the presence of gas in the formation is a definite possibility. It is beyond the scope of this study to investigate further the exact cause of this behavior in density and neutron logs.

As indicated above, there are CO₂-bearing zones in Cerro Prieto, and many density-neutron logs from the field have zones that exhibit curve separation indicative of the presence of gas. After the necessary environmental corrections have been made to the density and neutron curves, the gas effect is more pronounced than on the East Mesa logs after correction. There is further discussion of this effect and a SARABAND example in Section 4.3.2 of this report.

6. The Sonic travel time values in the shale zones are greater than 100 microseconds and are normal for compacted shales. Above a depth of about 1200 to 1525 meters, shales appear under-compacted.

Sonic logs are usually not run at Cerro Prieto because the upper geological section is composed of unconsolidated deltaic sediments and acoustical-type logs normally give poor results in these types of formations because of their lack of compaction. Also, if the drilling mud is cut by carbon dioxide or other gases, acoustic log quality will be extremely poor, as the gas attenuates the acoustic signal thereby making detection of the signal unreliable.

7. There have been several dipmeter logs run in East Mesa and they have yielded very useful results. They have been helpful in structural mapping and

in the location of faults. The predominant dip direction in East Mesa wells 8-1 and 6-2 near the central part of the anomaly is approximately SSE, whereas wells 31-1 and 5-1 near the "flanks" of the anomaly appear to have a westerly dip direction. This may indicate a possible fault between the central part and the flank.

Very few dipmeter logs have been run in Cerro Prieto, and no publications were found that indicated that any dipmeter data were used in studies of the field. We were unable to obtain any of the dipmeter logs or computed results. The temperature limitation on the dipmeter logging tools is probably the major reason that more dipmeter logs have not been run in this field.

4.3 Assessment of Interpreted Data

4.3.1 Literature Survey. Available literature on detailed interpretation of East Mesa well logs consists primarily of two studies:

1. An interpretive study of the well logs from East Mesa wells 5-1, 8-1, 6-1, 6-2, and 31-1 by TRW/Intercomp, Inc. prepared as a part of a general study of this reservoir for the Bureau of Reclamation. The work is contained in TRW Systems Group (1976a).
2. An interpretive study of the logs from three of the Republic Geothermal wells (16-29, 18-28 and 38-30) and four older abandoned wells (Magma Sharp, Shafer Barbara, Texaco Grupe-Engelbretson, and American Petrofina USA #27-1) prepared by TRW/Intercomp, Inc. under a contract to the US Energy Research and Development Administration. The work is contained in TRW Systems Group (1976b).

The log analysis portions of these two studies consisted primarily of determinations of porosity, permeability, and sand content by a shaly-sand interpretation approach.

There have been a few other publications that considered some limited aspects of the well logs from East Mesa. For example, Littleton and Burnett (1977) presented vertical profiles of formation water salinities calculated from both spontaneous potential and electrical resistivity logs from ten East Mesa wells. These wells were: 6-1, 6-2, 8-1, 5-1, and 31-1 of the US Bureau of Reclamation; 18-28, 16-29, and 38-30 of Republic Geothermal; and 44-7 and 48-7 of Magma Power Company. Littleton and Burnett (1977) is the only published information on the Magma Power wells 44-7 and 48-7.

It should be pointed out that before these studies were made, Schlumberger's SARABAND computer-processed interpretations were made for most wells. These computations may be considered the first interpretive work on East Mesa logs.

Swanberg (1975), Fournier (1973), Fournier (1976), Black (1975), and Hoagland (1976) used log data, particularly computer-processed interpretations such as SARABAND in their studies. Swanberg (1975) attempted to correlate all geophysical and geochemical data, both surface and downhole, with the well log information. He developed a conceptual model of the East Mesa reservoir from this study. Fournier (1973) and Fournier (1976) presented x-ray and optical studies of the drill cuttings from East Mesa wells 6-1 and 6-2, respectively. Hoagland (1976) used both SARABAND interpretations and drill cuttings in a geochemical study of the East Mesa reservoir.

Black (1975) utilized SARABAND log interpretations, as well as induction and temperature logs from East Mesa in an attempt to decipher the nature of the reservoir. Approximate salinities were computed from resistivity logs and

salinity profiles were correlated between various wells. An attempt was then made to use this salinity correlation to determine the subsurface flow directions.

Enrique Tolivia M. (date unknown) performed a study in which he made statistical correlations on different strata of the lithological column of Cerro Prieto geothermal wells in order to establish a tri-dimensional model of the geothermal zone. SARABAND and the spontaneous potential curve were used for the correlations. Abril G. and Noble (1978) and Prian C. (1978) used temperature and electrical logs for correlation and structural interpretation. These studies were made to better define the producing intervals and to provide improved planning for field development. There have been several other studies made in Cerro Prieto that were not obtainable for this project. In at least two of these studies, stratigraphic correlations were made based upon electrical logs and on lithological columns made up from the analyses of cuttings and cores recovered during drilling.

4.3.2 Comments on Interpretive Data. In all interpretive studies of the East Mesa reservoir an apparent lack of well-to-well correlation of logs is pointed out. This situation is caused by the complex, deltaic nature of the sediments and the high level of tectonic activity in this area. According to TRW Systems Group (1976a), the only reliable well-to-well correlations are in the northern part of the reservoir where excellent correlation is reported between wells 31-1 and 38-30.

A discussion of the analysis of dipmeter logs from several East Mesa wells is also contained in TRW Systems Group (1976a). The wells from which the dipmeter data were analyzed are 6-2, 5-1, 8-1, and 31-1. Figure 4.2 provides a summary of the interpreted dipmeter data. It is apparent from this figure that wells 6-2 and 8-1 in the central part of the field have a southeasterly dip, while wells 5-1 and

Fig. 4.2

EAST MESA DIPMETER DATA (From TRW Systems Group 1976a)

31-1 on the flank of the reservoir show a generally westerly dip. The same finding is reported by Swanberg (1975) and shown in Fig. 4.3, which is a stereonet plot of dip direction and magnitude. This has been considered as an indication of a fault between these two well pairs.

SARABAND and CORIBAND* Interpretations. SARABAND and CORIBAND are Schlumberger interpretational models used in sandstone and complex lithologies, respectively. SARABAND interpretations have been made on most East Mesa wells and CORIBAND interpretations have been made on a few. SARABAND has also been used on some of the Cerro Prieto wells. These models are computer-processed models that use various log combinations (resistivity, density and neutron logs are required as minimum input) and sophisticated interpretation techniques. In addition to their standard computed log presentations, Schlumberger developed a salinity computation particularly for geothermal well applications. This takes the form of a continuous curve of computed ppm of NaCl equivalent and is presented on both SARABAND and CORIBAND.

Several comments can be made concerning the SARABAND and CORIBAND logs from East Mesa and Cerro Prieto:

1. As has been pointed out before, a comparison of the density and neutron logs from East Mesa indicates that free gas saturation may exist in some zones. This observation is supported by similar occurrences of gas in the Cerro Prieto and Salton sea geothermal fields, which are in the same physiographic province. When evaluating the logs as recorded in the field, environmental corrections should be made in addition to those automatically made while logging. In particular, the correction for temperature may become significant in very hot wells. This temperature correction adds to the neutron value and, in some cases,

*A Schlumberger trademark.

STEREO NET PLOTS OF DIP DIRECTION AND MAGNITUDE

(From Swanberg 1975)

Fig. 4.3

will greatly reduce or even eliminate the "apparent" gas effect. These corrections are routinely made prior to the processing of the SARABAND or CORIBAND interpretations.

The salinity value is a conversion from an R_{wa} (apparent formation water resistivity) computation that takes into account the following formation characteristics:

Porosity corrected for shale content

Shale content

Shale resistivity

Formation resistivity

(See Poupon et al. 1970)

A Simandoux water saturation equation is used where water saturation is assumed to be 100% and the only remaining unknown is R_w (the formation water resistivity). If carbon dioxide or another gas is present, the resulting computed salinity will be too low in value. To directly evaluate the gas saturation in such cases, R_w is a required input. This can be estimated from the SP curve if the water is predominately an NaCl solution.

Figure 4.4 is a reproduction of part of a SARABAND computed on well M-27 in Cerro Prieto. The salinity curve shows an average ppm of NaCl equivalent of 17 000 over the lower half of a sand and an average ppm of 4000 over the upper half. The resistivity log shows an increase from 1-1.5 ohm-meters in the lower part of the zone to 5-9 ohm-meters in the upper part of the zone. The neutron porosity (not corrected for temperature) reads lower than the density porosity throughout the entire sand section but is reduced by an additional six porosity units in the upper half. It is strongly felt that this is caused by carbon dioxide in the formation.

M27 - CERRO PRIETO

PARTIAL SARABAND LOG

Fig. 4.4

The conversion of an Rw_a value to ppm of NaCl equivalent requires definition of the temperature at each computation. Usually, a constant geothermal gradient is assumed as determined from the BHT (Bottom Hole Temperature as measured at the time of logging), surface temperature, and depth reference. If significant temperature anomalies exist at the time of logging, the computed salinity may be either too high or too low, depending on the actual temperature at the depth of the computation.

2. The SARABAND logs present a "permeability index" profile. This concept evolved from an approach commonly used in the petroleum industry. Empirical correlations yielded the following equation:

$$k = \frac{C\phi^x}{S_{wi}^y}, \quad (4.1)$$

where k is the permeability, ϕ the porosity, and S_{wi} the irreducible water saturation of a reservoir rock, and C , x , and y , are empirical parameters. There are several versions of this relationship derived from core-analysis data. In petroleum reservoirs, the water saturation in the reservoir is usually equal to S_{wi} , except for the region of the reservoir in the "transition zone." Thus, knowing the parameters C , x , and y , permeability can be calculated from log-derived ϕ and water saturation.

In this situation where water saturation is assumed to be 100%, S_{wi} is set to a constant value which results in the equation:

$$k = C'\phi^x \quad (4.2)$$

This equation is very similar to most empirical relationships derived from core analysis or from core analysis combined with log data. Standard values for C, x, and y are used unless core data are available for matching. When core data are not used, the resulting permeability index may be quantitatively in error by some unknown magnitude, but the permeability index can still be valuable in comparing one zone to another. Consistently reliable calculations of permeability from logs will probably not be feasible until techniques are developed for defining formation characteristics such as grain size and sorting. When C, x, and y are determined from core analysis, the results can be quite good but are usually limited to a given field and geological interval.

TRW Studies on East Mesa (TRW Systems Group 1976a and 1976b) These studies include a detailed

computer-aided interpretation of logs from 12 wells in the East Mesa area. The log analysis included calculations of sand content, porosity, and permeability profiles in each well. The results of these studies are summarized in tables contained in Appendix C.

For estimation of sand content, one or more sand/shale discriminators are used. The following discriminators were used in the TRW studies:

1. Corrected gamma ray intensity.
2. The difference between neutron and density derived porosities.

The corrected gamma ray intensity was histogrammed and was also crossplotted against the difference between neutron and density log-derived porosities. From these two approaches a cutoff gamma ray value was chosen for sand. See Figs. 4.5 and 4.6 for a typical case (from Mesa 31-1). This technique

GAMMA LOG RESPONSE HISTOGRAM: MESA 31-1

(From TRW Systems Group 1976a)

Fig. 4.5

Fig. 4.6

CROSS PLOT OF NEUTRON - DENSITY LOG POROSITY DIFFERENCE
AND GAMMA LOG RESPONSE: MESA 31-1

(From TRW Systems Group 1976a)

was not possible for old wells where neutron and density logs were not available. This approach for sand/shale discrimination is a common one in the petroleum industry. However, there are two situations in which this approach will not be valid:

1. If the sand is radioactive, as when it contains abundant potassium mica or potassium feldspar or other radioactive components.
2. If the sand contains gas.

It should be pointed out that both of these conditions may be present in some zones in East Mesa wells. For example, Fournier (1973) reported potassium-rich feldspar in 92 out of 98 drill cutting samples from Mesa 6-1 studied by x-ray and optical microscopy. The weight percentage of K-feldspar (potassium-feldspar) ranged from 7% to 40%. However, 70% of all samples contained 15% or less K-feldspar. Fournier (1976) reported that of 89 drill cutting samples from Mesa 6-2 studied, 30 samples showed major amounts of K-feldspar, 12 showed moderate amounts, and 37 showed minor amounts. Thus, it is possible that the gamma ray log response may be affected by K-feldspar in at least some zones.

As has been pointed out in the previous subsection, the possible presence of gas saturated zones is indicated on some East Mesa Logs. In such cases, sand/shale discrimination from porosities based on neutron and density logs is not applicable. However, the gamma ray log is not affected by the presence of gas and a gamma ray histogram should remain an effective sand/shale discriminator in gas-bearing zones. The spontaneous potential log was not used as a sand/shale discriminator in this study because of the apparent drift of the SP base line with variation in water salinity from zone to zone.

For the five USBR wells, the TRW study (TRW Systems Group 1976a) indicates that porosities were calculated from the density log by using an empirical transform (equation):

$$\emptyset = 1.57 - 0.59\rho, \quad (4.3)$$

where $\emptyset$ is porosity and ρ is the density log response. This transform was developed from a plot of density log response vs core-derived porosity at the corresponding depths from Mesa 5-1 well (Fig. 4.7). As is evident from this figure, the data base is limited (21 points) and shows a great deal of scatter. Since the data points are clustered between 20 to 30% porosity, a least-squares fit through the data is unreliable. In order to improve the correlation, the least-squares line fitted to these points was also constrained to pass through the point corresponding to zero porosity, a point at which ρ becomes equal to ρ_{ma} (density of the rock matrix). The ρ_{ma} value was obtained by averaging the grain densities measured on core samples. In developing this technique, a ρ_{ma} of 2.66 g/cm^3 and a fluid density (ρ_f) of 0.98 g/cm^3 were used as opposed to the values of $\rho_{ma} = 2.65 \text{ g/cm}^3$ and $\rho_f = 1.00 \text{ g/cm}^3$ usually used for porosity calculations in sandstone.

The above approach is reasonable, except that Eq. (4.3) is based on very limited data from a single well. Considering the large variation in shaliness and the indications of several distinct depositional environments in these sands, such a transform is questionable for general use. The report (TRW Systems Group 1976a) does point this out. However, it is not clear why more core data from the USBR wells were not used in arriving at the transform and thereby possibly improving its reliability. The list of core data from the USBR wells (see Table C-IV) shows that there were some core data available from wells 6-1, 8-1, and 31-1. It should be noted that nine out of the ten core samples from well 6-1 (Table C-IV) show measured grain densities (ρ_{ma})

CORE POROSITY - DENSITY LOG RESPONSE
 RELATIONSHIP: MESA 5-1
 (From TRW Systems Group 1976a)

Fig. 4.7

higher than the 2.66 g/cm^3 used in the transform. These high values of ρ_{ma} may be due to the presence of primary heavy minerals or to hydrothermal alteration. Whatever the origin of high ρ_{ma} in well 6-1, the use of Eq. (4.3) on this well should lead to underestimation of the porosity. However, the averaged ϕ values (averaged over each 76.2-m (250-ft section for well 6-1) reported by TRW do not show any apparent indication of having underestimated porosities. It can be shown that if a zone in well 6-1 has $\rho_{ma} = 2.80 \text{ g/cm}^3$, then the porosity calculated by Eq. (4.3), assuming a fluid density of 0.98 g/cm^3 , will be lower than the true porosity by an amount ($\Delta\phi$) given by:

$$\Delta\phi = 0.04\rho - 0.03. \quad (4.4)$$

Thus, for a zone whose porosity is calculated by Eq. (4.3) to be 20% ($\rho = 2.32 \text{ g/cm}^3$), $\Delta\phi = 0.06$ and the true porosity is 26%. The underestimation in porosity for zones with high ρ_{ma} may be at least partially mitigated by overestimation of porosity for zones with ρ_{ma} lower than the average of 2.66 g/cm^3 . But as pointed out before, in Mesa 6-1, none of the ten core samples showed ρ_{ma} less than 2.66 g/cm^3 . If the cores from well 6-1 are representative, the porosities in the well are underestimated.

Conventional shaly-sand analysis techniques (similar to SARABAND) were used in the two TRW reports (TRW Systems Group 1976a and 1976b) for estimating porosities in the three Republic Geothermal wells (38-30, 16-29, 18-28). This approach was taken because the porosities calculated by Eq. (4.3) were felt to be too high. In particular, it was found that the porosities were too optimistic in shaly sands. This led to the speculation that the cored sands used in developing the transform were probably clean, that is, shale-free. It was also noted that even if some clay minerals existed in the core they might have dried out in

the core handling and preparation process, thus indicating an unduly high porosity during measurement. This led the investigators to use the conventional shaly-sand porosity calculation technique based on density and neutron logs in preference to the use of the density log and the transform. The same reason might have also caused the porosity values from other East Mesa wells to be too high since they were computed using Eq. (4.3).

In summary, the following characteristics must be considered when using core analysis to develop porosity relationships with logs for application to sand/shale formations:

Typically, the cleanest (most shale-free) portion of a core is selected for evaluation. Relationships established from these data will result in porosities too high except in clean intervals.

Even when core analysis is performed on shaly samples, the preparation process will usually cause the porosities to be too high. (The clays may be dried out and some clay actually removed when saturating the core with fluids.)

Transforms established from a set of data are valid for application to other wells only when the matrix, shale content, and fluids are the same as those in the well or wells from which the transform was derived. The use of the transform on a well that has a different matrix from some depositional feature will yield computed porosities higher (or lower) than they should be.

In shaly sandstone formations such as East Mesa, the shale content and porosity can vary over a wide range. Unless many costly cores are available,

the most economical and accurate reservoir evaluation method will probably be a shaly sand log interpretation technique.

The permeability in all East Mesa wells was calculated by another empirical transform (equation) based on core data (TRW Systems Group 1976a):

$$\log k_h = 13.614 \phi - 1.8126, \quad (4.5)$$

where k_h = reservoir horizontal permeability. Figure 4.8 shows the plotted data points used in the derivation of this equation. Although the data set is small, this transform appears to have a reasonable degree of correlation and is spread over a large range of ϕ and k values. This transform appears to have included all available core data from the USBR wells (see Table C-IV). It should be noted that two points in Fig. 4.8 fall outside the general trend. These points correspond to the 2135.7-2136 m (7007-7008 ft) and 2136.3-2136.6 m (7009-7010 ft) zones, respectively. For their porosities (17.2 and 20.2%, respectively) these zones have much lower permeabilities (0.033 and 0.28 md, respectively) and much higher matrix densities (2.843 and 2.840 g/cm³, respectively) than the other zones represented on the figure. It is probable that these two zones have undergone a loss of permeability (but not necessarily any significant loss in porosity) as a result of hydrothermal alteration and/or mineral deposition. Core analysis data appear to indicate similar possibilities for the zones at 776.6-793.4 m (2548-2603 ft) and 2129.9-2147.3 m (6988-7045 ft) in well 6-1.

Although Eq. (4.5) is reasonable, the k values were calculated from this transform by log-derived porosity values. As pointed out earlier, the log-derived porosity values for most USBR wells, having been derived by Eq. (4.3), are likely to be in error, at least in shaly zones. Thus, k

CORE POROSITY - HORIZONTAL PERMEABILITY RELATIONSHIP
(From TRW Systems Group 1976a)

Fig. 4.8

values for most of the zones are also likely to be inaccurate in those cases. For the Republic Geothermal wells, the porosity values derived from the shaly-sand analysis technique were used in Eq. (4.5). While this is reasonable, it must be noted that there is no real verification that the calculated shaly-sand porosities are more accurate.

A third core-data-derived transform was used in the study (TRW Systems Group 1976a) to estimate vertical permeabilities in all East Mesa wells:

$$\log k_v = 0.940 \log k_h - 0.0436, \quad (4.6)$$

where k_v is the vertical permeability and k_h is the horizontal permeability. Figure 4.9 presents the data points from which Eq. (4.6) was derived. As this figure shows, the equation is quite reasonable.

For the four older, abandoned wells (Magma Sharp, Shafer Barbara, Texaco Grupe-Engbretson, and American Petrofina USA #27-1) it was more difficult to achieve sand/shale discrimination. No gamma ray, density, or neutron logs were available on these wells; hence, TRW Systems Group (1976b) relied on SP and resistivity logs for sand/shale discrimination. By crossplotting SP and resistivity and histogramming SP values, a quantified shale cut-off was derived. However, the reliability of the SP data was reduced by base line drift, so the sand/shale discrimination in these wells was less reliable than in the newer wells.

Only one old well (American Petrofina USA #27-1) had a porosity log (Sonic). This log was used to derive porosity from Sonic response after applying a compaction correction. For the other wells, approximate porosity values were obtained by using Archie's formula:

$$\phi = (aR_w/R_t)^{1/m}, \quad (4.7)$$

CORE HORIZONTAL - VERTICAL PERMEABILITY RELATIONSHIP
(From TRW Systems Group 1976a)

Fig. 4.9

where R_t is the electrical resistivity of the formation completely saturated with a formation water of resistivity R_w , and a and m are empirical parameters with values in the order of 1 and 2, respectively. In using Eq. (4.7), TRW Systems Group (1976b) used the values of 1.13 for a and 1.73 for m . How these parameter values were chosen is not explained, but it is possible that a and m were calculated from other area wells for which both a porosity log and multiple resistivity logs were available. For example, ϕ in Eq. (4.7) can be obtained from a porosity log and (R_w/R_t) can be obtained from the shallow-investigation resistivity device by the relationship:

$$\frac{R_w}{R_t} = \frac{R_{mf}}{R_{xo}}, \quad (4.8)$$

for completely water saturated rocks, where R_{mf} is the electrical resistivity of the mud filtrate and R_{xo} is the resistivity of the zone around the well flushed by mud filtrate. Thus, statistically representative a and m values can be derived from some wells. In any case, it is obvious that porosities calculated for the four old wells are less reliable than those of the newer wells.

The salinity of a geothermal water is an indication of its quality as regards possible problems of scaling, corrosion, and disposal. Salinities can be estimated from logs but were not reported in the TRW Systems Group (1976a) report. However on the basis of a Gamma Ray - SP Z plot (where Z axis represents depth) they inferred that the well 31-1 displays a salinity reversal at 1158.2 m (3800 ft). Above that level, salinity increases with depth whereas below that level, salinity decreases with depth for several hundred meters. Similar salinity reversals have been indicated in other wells by the SARABAND logs.

Littleton & Burnett (1977) Study. Salinity profiles were computed from SP and dual induction logs for 10 East Mesa wells. Salinities (in parts per million of NaCl equivalent) were estimated from log-derived R_w values using standard R_w vs NaCl salinity data for various temperatures. R_w had been evaluated in two independent ways:

1. From the SP log using the conventional SP equation:

$$SSP = -(60 + 0.133T) \log R_{mf}/R_w, \quad (4.9)$$

where SSP is the static spontaneous potential in millivolts and T is the formation temperature in °F.

2. From the dual induction log using Eq. (4.8).

The salinities calculated by the two methods showed general agreement in trend although SP-derived salinities were consistently higher than resistivity-derived salinities by as much as several thousand parts per million. Figures 4.10 through 4.12 show the salinity profiles calculated for the East Mesa wells by Littleton & Burnett (1977). In these figures, SPPM indicates the SP-derived profile, RPPM indicates the resistivity-derived profile, and the heavy line gives the profile of the average between SPPM and RPPM.

There may be several possible problems with these salinity calculations:

1. SP base line shifts may make estimation of static spontaneous potential difficult.
2. Presence of streaming potential on the SP curve (Hill 1959) is likely, particularly in shallower zones. This would increase the total SP, causing overestimation of salinity.

Fig. 4.10

MESA ANOMALY
CHEMICAL PROFILE OF GEOTHERMAL WELLS

(From Littleton and Burnett 1977)

FIG. 4.11

NOTE: Compilation and Interpretation by:
Robert T. Littleton and Earl E. Burnett
U.S. Bureau of Reclamation
Lower Colorado Region

MESA ANOMALY
CHEMICAL PROFILE OF GEOTHERMAL WELLS (cont'd)

(From Littleton and Burnett 1977)

Fig. 4.12

NOTE: Compilation and Interpretation by:
 Robert T. Littleton and Earl E. Burnett
 U.S. Bureau of Reclamation
 Lower Colorado Region

MESA ANOMALY
 CHEMICAL PROFILE OF GEOTHERMAL WELLS (cont'd)

(From Littleton and Burnett 1977)

3. Calculations here assume a completely water saturated formation which is not possible if there is some gas present. Nevertheless, it is obvious from Figs. 4.10 through 4.12 that each well has a pronounced reversal in salinity at a depth of about 760 to 915 m (2500 to 3000 ft). (For a further discussion of the salinity profile reversal phenomenon, see Section 4.4.5.)

4. Salinity estimates from SP or resistivity logs are based on the assumption of a NaCl brine, which is not necessarily true for all geothermal waters, particularly ones with low total dissolved solids.

4.4 Special Problems - Temperature Effects

4.4.1 Horizontal Resistivity Profiles. The resistivity of a porous and permeable formation will exhibit a change horizontally outward from the drill hole due to invasion into the formation by the liquid from the drilling mud. Invasion varies in penetration distance and shape depending on such variables as:

- mud weight
- formation pressure
- mud fluid loss
- time formation exposed to drilling fluid
- porosity
- permeability
- fluid content in formation.

Figure 4.13 is an example of a resistivity profile caused by invasion of mud filtrate.

STEP PROFILE

Fig. 4.13

On Fig. 4.13, the abbreviations used are as follows:

- R_m is mud resistivity.
- R_{xo} is resistivity of flushed zone.
- R_t is resistivity of uncontaminated zone.
(this value is designated as R_o if only water fluids are involved).
- d is hole diameter.
- d_i is invasion diameter.

Figure 4.13 is a classic "step" profile, meaning that resistivity changes abruptly from R_{xo} to R_t with a sharp step resulting in a thin horizontal transition zone. This simplifying model allows the prediction of response for resistivity curves with different radii of investigation. In reality, a transition zone exists which is a gradation of the mixture of mud filtrate and formation water. This zone can be very narrow or wide depending on many variables noted previously.

If a "step" profile is assumed, a solution to the calculation of R_{xo} , R_t , and d_i values can be obtained by an iterative solution of the following simultaneous equations:

$$\frac{1}{R_D} = \frac{G_D}{R_{xo}} + \frac{1-G_D}{R_t}, \quad (4.10)$$

$$\frac{1}{R_M} = \frac{G_M}{R_{xo}} + \frac{1-G_M}{R_t}, \quad (4.11)$$

$$\frac{1}{R_S} = \frac{G_S}{R_{xo}} + \frac{1-G_S}{R_t}, \quad (4.12)$$

where:

- R_D is Deep reading resistivity device.
- R_M is Medium reading resistivity device.
- R_S is Shallow reading resistivity device.

G_D , G_M , & G_S are constants related to the above devices. They are dependent on specific tool design and the d_i being considered.

In addition to the effects of invasion of drilling fluid on resistivity, a change in temperature horizontally occurs as a result of the cooling effects of circulating drilling mud past the formations in the process of drilling the well. This mud is cooler than the formation and thus acts as an absorber or "sink" to withdraw heat from the formation. The amount of heat withdrawn is a function of mud temperature, formation temperature, and length of time that mud is circulated past the formation. This problem is present in all wells drilled but is usually considered minimal. However, when drilling sedimentary or ash flow geothermal wells, the effect is increased as a result of a greater difference between formation and mud temperatures.

In the Cerro Prieto field, this effect is further amplified by the practice of "icing down" the drilling mud. In order to prolong the time that a logging tool will operate in a geothermal well before the heat effects stop or distort its measuring system, cakes of ice are placed in the mud tanks or pits so that the mud temperature is considerably reduced. This results in further increasing the difference between hole and formation temperatures. The errors this temperature effect produces on measurements or calculations of R_t has been of concern for some time to those attempting to evaluate the formations using logs. The following is a study of this problem to investigate the real extent of its effect on log measurements.

The top portion of Fig. 4.14 shows a typical calculated temperature cross section of the East Mesa 5-1 well at a depth of 762 m (2500 ft). Calculated temperatures are plotted on the ordinate vs distances in terms of diameters (concentric to borehole) on the abscissa.

Fig. 4.14

<u>Diameter</u>	<u>Temperature</u>
0.27 m (10.5 in.)	104.8°C. (220.7°F)
0.64 m (25 in.)	118.3°C. (245°F)
1.27 m (50 in.)	131.8°C. (269.2°F)
1.90 m (75 in.)	137.7°C. (279.9°F)
2.54 m (100 in.)	140.9°C. (285.6°F)
3.81 m (150 in.)	141.4°C. (286.4°F)
5.08 m. (200 in.)	142.9°C. (289.2°F)
6.20 m (245 in.)	143.3°C. (289.9°F)
6.35 m (250 in.)	143.3°C. (289.9°F)

The calculated value of the diameter where the temperature reaches static is 6.2 m (245 in.). However, this large diameter can be misleading. As shown by the temperature profile, the change in temperature is less than 0.5°C between a diameter of 3.8 m (150 in.) and the point where it reaches maximum. The calculated diameter where a temperature is 95% of the difference between hole temperature and original formation temperature was calculated. This diameter is 2.6 m (103 in.) for a temperature of 141.4°C (286.4°F). The temperature profile was determined for 2.83 hours after circulation was stopped. This is the estimated time that the Dual Induction-Laterolog 8 was recorded at this depth after circulation ceased.

The lower half of Fig. 4.14 shows the temperature effect on the formation resistivity. This correction was calculated by considering the formation as a series of annular volumes between concentric cylinders. An average temperature for each annular zone was established and resistivity corrections were made for each zone. It is important to determine whether a specific annular space lies either partially or totally within the diameter of filtrate invasion. That is, does it belong in the R_{xo} or R_t region? A step profile was assumed and a d_i was determined using the method

described earlier employing Eqs. (4.10), (4.11), and (4.12). Temperature effects were ignored for this portion. This d_i value was 0.87 m (34.4 in.). Temperature effects on resistivity values can be made using the temperature vs conductive liquids relationship.

$$R_B = R_A \frac{(T_A + 21.5)}{(T_B + 21.5)}; \text{ } ^\circ\text{C} , \quad (4.13)$$

OR

$$R_B = R_A \frac{(T_A + 7)}{(T_B + 7)} ; \text{ } ^\circ\text{F} . \quad (4.14)$$

The following equations can be used to calculate the temperature effects according to the geometry shown in Fig. 4.14.

$$\frac{1}{R_D} = \frac{G_h}{R_M} + \frac{G_1}{R_{xO}} \frac{(T_1 + 7)}{(T_F + 7)} + \frac{G_2}{R_{xO}} \frac{(T_2 + 7)}{(T_F + 7)} + \frac{G_3}{R_t} \frac{(T_3 + 7)}{(T_F + 7)} + \dots + \frac{G_n}{R_t} \frac{(T_n + 7)}{(T_F + 7)} ; ^\circ\text{F} , \quad (4.15)$$

AND

$$\frac{1}{R_S} = \frac{G_h'}{R_M} + \frac{G_1'}{R_{xO}} \frac{(T_1 + 7)}{(T_F + 7)} + \frac{G_2'}{R_{xO}} \frac{(T_2 + 7)}{(T_F + 7)} + \frac{G_3'}{R_t} \frac{(T_3 + 7)}{(T_F + 7)} + \dots + \frac{G_n'}{R_t} \frac{(T_n + 7)}{(T_F + 7)} ; ^\circ\text{F} , \quad (4.16)$$

where G_1 , G_2 , etc. and G_1' , G_2' , etc. can be calculated as follows:

$$\begin{aligned}
G_1 &= G_{25} - G_h \\
G_2 &= G_{di} - 25 \\
G_3 &= G_{50} - G_{di} \\
G_4 &= G_{75} - G_{50} \\
G_5 &= G_{100} - G_{75} \\
G_6 &= G_{150} - G_{100} \\
G_7 &= G_{200} - G_{150} \\
G_8 &= G_{dt} - G_{200} \\
G_9 &= 1 - G_{dt}
\end{aligned}$$

where:

G_h is geometrical factor for borehole
 G_{di} is geometrical factor for invaded zone (fluid)
 G_{dt} is geometrical factor for temp. change zone
 G_{25} is geometrical factor for 25" cylinder
 G_{50} is geometrical factor for 50" cylinder
 etc.

Thus:

$$G_1 + G_2 + G_3 + \dots G_n = 1 .$$

The above geometrical factors are for the deep resistivity device, the deep Induction log in this case. A prime (') mark indicates that the geometrical factors are for the shallow device, the Laterolog-8 in this case.

Log values from East Mesa 5-1 at a depth of 762 m (2500 ft) were used to make a comparison of resistivities calculated by: (1) making corrections for invasion only, and (2) making corrections for invasion and temperature. The raw log value from the deep induction is:

$$R_{ild} = 1.71 \text{ ohm-m} .$$

Ignoring the temperature profile and correcting only for invasion using Eqs. (4.10), (4.11), and (4.12):

$$R_t = 1.69 \text{ ohm-m} .$$

Correcting for both temperature and invasion using Eqs. (4.15) and (4.16):

$$R_{t_c} = 1.63 \text{ ohm-m} .$$

R_t was computed for all values from 320-1829 m (1050-6000 ft) and the results crossplotted. Figure 4.15 is a crossplot of R_t vs R_{ILD} , and Fig. 4.16 shows the statistical data associated with the crossplot. Figure 4.17 is a crossplot of R_{t_c} vs R_t and Fig. 4.18 shows the statistical data associated with that crossplot.

4.4.2 Conclusions About Resistivity Profiles. When medium to low (10 ml or less) water loss muds are used as drilling fluids, the filtrate invasion diameter is small, thus corrections for fluid invasion are minimal.

The temperature profile studied here indicates that the effects of temperature change by conduction need not present a problem as long as enough data is available to determine true or initial formation temperature. If the temperature profile deviates radically from a linear relationship with depth, this profile must be considered.

In the example used here (Mesa 5-1), a variation of R_t from measured resistivity, R_{ILD} , of less than 1% was noted. This includes correction for both temperature and fluid changes in the invaded zone. If the temperature differential between hole and undisturbed formation is

WELL NUMBER 22001
1 DROP

LOGCALC RESULTS
TOP OF INTERVAL (TOPD) = 1050.00

02/21/79 09 09 57
BOTTOM OF INTERVAL (BOTD) = 6000.00

Fig. 4.15

A = 10, B = 11, C = 12, . . . , Z = 35

WELL NUMBER 22001
1 DROP

LOGCALC RESULTS
TOP OF INTERVAL (TOPD) = 1050.00

02/21/79 09 09 57
BOTTOM OF INTERVAL (BOTD) = 6000.00

MEAN AND STANDARD DEVIATION
FOR ALL POINTS IN FREQUENCY CROSSPLOT

		MEAN	STD DEV	
		----	-----	
X AXIS =	RTC	3.385	2.195	RTC
Y AXIS =	RILD	3.420	2.176	RILD

Y VS X

COHR. COEFF. = 0.9991

X VS Y

	LST SQ	RMA		LST SQ	RMA
SLOPE	0.99137	0.99137	SLOPE	1.00871	1.00870
X-INTERCEPT	-0.06505	-0.06502	X-INTERCEPT	-0.06505	-0.06502
Y-INTERCEPT	0.06448	0.06446	Y-INTERCEPT	0.06448	0.06446
STANDARD ERROR	0.06731	0.06702	STANDARD ERROR	0.06731	0.06761

NUMBER OF POINTS CROSSPLOTED	4143
POINTS DROPPED FOR PRINTER DROP	19
POINTS WITH OFFSCALE X VALUES	0
POINTS WITH OFFSCALE Y VALUES	0
POINTS WITH OFFSCALE X AND Y	0
POINTS WITH NULL X OR Y	0
POINTS ON ALREADY-FULL PRINTER SPOTS	789
POINTS BEYOND TABLE OVERFLOW	0
TOTAL	4951

Fig. 4.16

WELL NUMBER 22001
1 DROP

LOGCALC RESULTS
TOP OF INTERVAL (TOPD) = 1050.00

02/21/79 09 09 57
BOTTOM OF INTERVAL (BOTD) = 6000.00

Fig. 4.17

A = 10, B = 11, C = 12, . . . , Z = 35

WELL NUMBER 22001
1 DROP

LOGCALC RESULTS
TOP OF INTERVAL (TOPD) = 1050.00

02/21/79 09 09 57
BOTTOM OF INTERVAL (BOTD) = 6000.00

MEAN AND STANDARD DEVIATION
FOR ALL POINTS IN FREQUENCY CROSSPLOT

	MEAN	STD DEV	
	----	-----	
X AXIS = RTC	3.384	2.194	RTC
Y AXIS = RT	3.415	2.172	RT

Y VS X

CORR. COEFF. = 0.9992

X VS Y

	LST SQ	RMA		LST SQ	RMA
SLOPE	0.98982	0.98983	SLOPE	1.01029	1.01028
X-INTERCEPT	-0.06547	-0.06544	X-INTERCEPT	-0.06547	-0.06544
Y-INTERCEPT	0.06480	0.06478	Y-INTERCEPT	0.06480	0.06478
STANDARD ERROR	0.06234	0.06202	STANDARD ERROR	0.06234	0.06266

NUMBER OF POINTS CROSSPLOTTED 4150

POINTS DROPPED FOR PRINTER DROP	17
POINTS WITH OFFSCALE X VALUES	0
POINTS WITH OFFSCALE Y VALUES	0
POINTS WITH OFFSCALE X AND Y	0
POINTS WITH NULL X OR Y	0
POINTS ON ALREADY-FULL PRINTER SPOTS	784
POINTS BEYOND TABLE OVERFLOW	0

TOTAL 4951

Fig. 4.18

greater, as it is in the Cerro Prieto field, a larger correction for temperature effects can be expected. This correction should still not be extreme, however, as long as filtrate invasion is controlled. A procedure for making these corrections is outlined later in this report.

4.4.3 Convection vs. Conduction of Heat. The effects of convection of heat on resistivity profiles has not been studied here. However, since this effect in a nonfractured reservoir can be directly related to the physical fluid invasion it should be easily minimized by a good mud system.

Conduction of Heat. Let us consider what happens regarding conduction in the drilling of a well. The moment the bit penetrates a formation, heat is withdrawn from the formation into the drilling mud. As long as the formation is hotter than the mud being circulated, this mud may be considered as an infinite heat sink. The result is that a given quantity of heat has been removed from the formation and the temperature profile is exponential with distance into the formation (until the original formation temperature is reached) as shown in Fig. 4.14.

After circulation has been stopped, the formation starts to heat up again. If we consider that the source of heat in the formation is infinite compared with the heat loss previously encountered, we can apply Kelvin's equation to calculate the temperature at any given distance r and any given time t :

$$T_{(r,t)} = T_i + \frac{C_1 \cdot q}{k' \cdot h} E_i - \frac{C_2 \cdot C_p \cdot r^2}{k' \cdot t}, \quad (4.17)$$

where:

$T_{(r,t)}$ is Temperature at distance r and time t .

T_i is initial formation temperature.

C_1 & C_2	are	constants depending on geometry and units.
q	is	heat flow rate (sign (+/-) must be defined as in or out of the formation).
k'	is	thermal conductivity.
h	is	height of unit studied.
ρ	is	formation density.
C_p	is	specific heat of formation and pore fluids.
$E_i(-x)$	is	the exponential integral of a function of $-x$.
r	is	distance into the formation.
t	is	time of heat withdrawal.

If we measure the temperature in the hole at several times after heat withdrawal (mud circulation) has stopped we can apply the method of Horner in the pressure buildup analysis to the computation of T_i (Dowdle 1975 and Crosby 1977). The following equation applies:

$$T_{(r,w)} = T_i + \left(\frac{C_1 \cdot q}{k' \cdot h} \right) \cdot \ln \left(\frac{t + \Delta t}{\Delta t} \right) \quad (4.18)$$

where Δt is the time since circulation until temperature $T_{(r,w)}$ is measured.

If we have several temperatures with respective Δt measurements, we can apply the technique of extrapolating to a $\ln \left(\frac{t + \Delta t}{\Delta t} \right)$ value of 1 to obtain a value of T_i , the initial or undisturbed formation temperature.

As shown in Fig. 4.19, the slope of the line is equal to:

$$\text{slope} = \frac{C_1 \cdot q}{k' \cdot h} \quad (4.19)$$

This technique is valid as long as the assumption that no further heat loss takes place during the process of reheating

Temperature Build Up

Fig. 4.19

the formation is true. This is not exactly the case because heat is still flowing into the hole. However, because the mud is not being circulated, the mud column is being heated and the differential temperature between hole and formation is consistently lessening, which results in minimizing the heat loss.

Some arguments have been made that these points on Fig. 4.19 will not fall in a straight line. The data shown here, from a well in Roosevelt Hot Springs field in Utah, seem to dispel that argument.

In the case of "icing down" the mud system as is common practice in Cerro Prieto, or multiple withdrawal periods, such as long interruptions in the circulation of mud, Eq. (4.18) is not applicable because the time, t , is not a single value. Instead a multiple rate buildup must be considered. This technique is well described by Edwardson et al. (1962). A two-rate equation can be developed as shown:

$$T_{(r,t)} = T_i - \left(\frac{q_2}{k' \cdot h} \right) \cdot \left[\left(\frac{q_1}{q_2} \right) \cdot \ln \left(\frac{t_2 + \Delta t}{t_2 - t_1 + \Delta t} \right) + \ln \left(\frac{t_2 - t_1 + \Delta t}{\Delta t} \right) \right] \quad (4.20)$$

where q_1 and q_2 represent different heat flow rates for respective time periods t_1 and t_2 .

$$\frac{q_1}{q_2} = \frac{T_1}{T_2} \quad , \quad (4.21)$$

where T_1 and T_2 are the changes in temperature during the respective times t_1 and t_2 . Here the entire term in brackets, $[]$, is plotted in the x axis on a logarithmic scale to determine T_1 and the slope. Once T_1 and the slope

have been established, a solution for the $E_1(-x)$ can be made from Fig. 4.19. The sign $(-x)$ can be evaluated from exponential integral tables.

The formation density can be obtained from the density log, and specific heat can be estimated satisfactorily by the following equation:

$$C_p = \emptyset \cdot C_w + (1 - \emptyset) \cdot C_m \quad , \quad (4.22)$$

where:

$\emptyset$ is porosity from the density log.
 C_w is the specific heat of water.
 C_m is the specific heat of the matrix rock--in this case, quartz.

Thus k' becomes:

$$k' = \frac{C_2 \cdot \rho \cdot C_p \cdot r^2}{(-x) \cdot t} \quad , \quad (4.23)$$

Note: the sign of $(-x)$ is not really negative here but defines a specific function.

It follows then that:

$$q = \frac{k' \cdot h}{C_1} \quad , \quad (4.24)$$

where h is considered as the unit vertical height and is equal to the vertical increment being used.

The prime use of a corrected R_t value is to derive a more accurate salinity profile with depth. A suggested equation for this conversion is:

$$R_w = \frac{R_t \cdot R_{sh} \cdot \emptyset_e^2}{0.8 \cdot (R_{sh} - V_{sh} \cdot R_t)} \quad . \quad (4.25)$$

(when $S_w = 100\%$)

and $\text{ppm} = 10^x$, (4.26)

where:

$$x = \frac{3.562 - \log (R_{w75} - 0.0123)}{0.954} \quad (4.27)$$

where:

R_{sh} is shale resistivity.
 ϕ_e is effective porosity.
 V_{sh} is shale fraction.
 R_w is apparent water resistivity at formation temperature.
 R_{w75} is water resistivity at 75°F.
 S_w is water saturation.

Convection of Heat. The amount of heat being removed from the formation because of replacement of formation waters by a cooler drilling fluid is directly related to the volume of rock containing this new fluid. This then is a function of both the porosity and the invasion distance. Again, if a low water loss mud is used, this effect is definitely minimized. One other consideration needs to be made. For heat withdrawal from the formation by conduction, the mud in the hole is constantly being replaced by circulation, resulting in a mud temperature (or "sink" temperature) that is reasonably constant. For convection, the heat "sink" is being heated rather rapidly because the respective volume of invaded zone compared to the balance of the formation is small. As the "sink" heats up, the differential temperature drops and heat transfer diminishes.

4.4.4 A Suggested Procedure and Computational Model for Geothermal Sand Reservoirs. If the following procedures are used, the logging data can be used to determine a great many parameters in the evaluation of a geothermal reservoir.

1. A reasonably accurate time vs depth record should be kept. Times when circulation is stopped and started are particularly important. This provides the data for the value t , or in the case of major interruption to the mud circulation, t_1 , t_2 , etc. Special note should be made as to the time and depth occurrences of any cooling or "icing down" of the mud system.
2. A bottomhole thermometer (at the least) should be run at the start of any major interruption of mud circulation, and again just before circulation is resumed. Again a record of the time is necessary.
3. When the well is logged, a continuous temperature log should be recorded prior to the running of the other logs. The time started and stopped are needed as part of the base data. Also, a record as to whether the log was recorded going into or coming out of the hole is needed. Recording the temperature log going into the hole has decided advantages.
4. Other logs should then be recorded. Again, a start-stop direction record should be kept and a maximum reading thermometer should be used on each device.
5. Another temperature log should be recorded as the last log.
6. If any interruption of the logging job is experienced, careful recording of the times should be made. This is especially true if circulation is resumed to either clean out or cool down the hole.

7. Any other pertinent data that might reflect the time, depth, or temperature history should be recorded and reported to those making a study of the reservoir logs.

The following calculations are suggested as a computational process to evaluate the full geothermal well. A computer is certainly recommended to perform these computations on a continuous basis.

1. Construct a time vs depth trace for the entire period of time that heat was being withdrawn from the formations. This is the variable t . If more than one heat withdrawal cycle is encountered, a separate trace for each cycle is needed as t_1 , t_2 , etc.
2. Construct a time vs depth trace for periods heat was being replaced in the formation up to the completion of the first temperature log. This will be Δt_1 .
3. Construct a similar trace associated with the running of the second temperature log. This will be Δt_2 .
4. Using the following equation, reconstruct the initial formation temperature, T_i :

$$T_i = T_1 + (T_2 - T_1) \cdot \frac{\ln \left(\frac{\Delta t_1 + t}{\Delta t_1} \right)}{\ln \left(\frac{\Delta t_1 + t}{\Delta t_1} \right) - \ln \left(\frac{\Delta t_2 + t}{\Delta t_2} \right)} \quad (4.28)$$

A plot of these temperatures at various times, T_o , T_1 , T_2 , and T_f is illustrated in Fig. 4.20.

5. The slope from the preceeding equation, Eq. (4.28), can be determined, and this becomes a

Temperature-Time Profile

Fig. 4.20

function of the heat flow to thermal conductivity ratio. See Eq. (4.19).

6. Equation (4.17) can then be solved for $E_i(-x)$.

7. Evaluation of the exponential integral for $(-x)$ results in the establishment of a trace for

$$x = \frac{C_2 \cdot \rho \cdot C_p \cdot r^2}{k' \cdot t} \quad (4.29)$$

8. Referring to Eq. (4.29), ρ can be obtained from a density log, C_p from Eq. (4.22), r from hole diameter divided by 2, t from time trace of Step 1, and C_2 a constant for units. Thus thermal heat conductivity, k' , can be calculated.

9. Equation (4.19) can now be used to obtain horizontal heat flow, q .

10. Use Eq. (4.17) to determine the temperature profile at time, t , and any radius, r . Fig. 4.21 is the plot of several temperature profiles at several distances (diameters in this case).

11. It is now possible to reconstruct the true value of R_t employing techniques outlined in Sec. 4.4.1. If the temperature difference $(T_i - T_1)$ is not unduly great and a low water loss mud has been used, this step may be unnecessary.

12. A salinity profile (NaCl equivalent) can now be calculated using Eqs. (4.25), (4.26), and (4.27).

13. V_{sh} and ϕ_e can be calculated in the conventional manner for sandstones. R_{sh} must be determined from log statistics.

Temperature - Distance Profile

°C

Fig. 4.21

14. An example of tabular listings are shown in Tables D-I, D-II, and D-III in Appendix D. Figures 4.22 and 4.23 show V_{sh} , ϕ_e , and matrix sand, shale mixture as well as the salinity profile comparison.

4.4.5 Salinity Profile Reversals. Much has been said about the possibility of salinity profile reversal. By this we mean an increase in salinity with depth down to a certain horizon and then a decrease with a further increase in depth. In addition to the salinity profiles illustrated in Section 4.3, the SARABAND salinity logs definitely indicate this phenomenon.

This effect was investigated further in this project by computer processing data from Mesa 5-1 using Scientific Software's LOGCALC log analysis system. Even after correcting R_t for the temperature profile and taking this nonlinear profile into account in the calculation of salinities, as was done in this study, the reversal remains evident.

Two sections of a computer-processed log are shown in Fig. 4.22 from depths of 747 m (2450 ft) to 808 m (2650 ft) and Fig. 4.23 from depths of 1372 m (4500 ft) to 1433 m (4700 ft).

The salinity profiles indicate the following:

Depth	ppm Temperature Correction	ppm Linear from BHT	Ratio of ppm Methods
716m (2530 ft)	7250	13800	1.90
1378m (4520 ft)	3800	5500	1.45
1411m (4530 ft)	2880	4170	1.45

This clearly shows a decrease in salinity by zone with depth and, in the lower case, a clear decrease in salinity within a short depth interval.

Fig. 4.22

Fig. 4.23

Note also that the ratio of salinities from the two methods indicates a greater error potential in the upper zone by using the linear approach to formation temperature estimation. This is reasonable because a strong temperature anomaly occurs at approximately 762 m (2500 ft). See Figs. 4.20 and 4.21.

A crossplot of the salinity based on the actual formation temperature profile vs salinity vs hole temperature profile is shown in Fig. 4.24 and vs a linear temperature profile in Fig. 4.25. Note that the slopes indicated on the plots are slopes of the logarithms of the values rather than the values themselves.

5. EVALUATION OF LOG INTERPRETATION

5.1 Usefulness of Interpretations. In spite of the shortcomings of logging hardware and interpretation techniques, it is apparent from our study that some log interpretations have been extremely useful in delineating geothermal reservoirs, as well as unraveling and quantifying their characteristics. It is fair to claim that of the three main sources of borehole data: logging, coring, and well testing, well logging has provided the most continuous and detailed information about the reservoir characteristics. Core data are sparse and well test analysis gives only averaged reservoir properties for a large part of the reservoir. Some specific instances of the proven utility of well log analysis in understanding and evaluating the East Mesa and Cerro Prieto reservoirs are enumerated below:

1. As pointed out in Section 4.3.2, interpretation of dipmeter logs proved valuable in deciphering the structure and locating faults between wells in the East Mesa area.

WELL NUMBER 22001
1 DROP

LOGCALC RESULTS
TOP OF INTERVAL (TOPD) = 1050.00

02/21/79 09 09 57
BOTTOM OF INTERVAL (BOTD) = 6000.00

PPM NaCl (in 1000's)
Based on
Hole Temperature Profile

Fig. 4.24

Fig. 4.25

2. Salinity profiles calculated from resistivity and SP logs were invaluable in identifying the salinity reversal in East Mesa wells. This salinity reversal, discussed in Section 4.4.4, has considerable significance in interpreting the characteristics of the reservoir. Salinities calculated from logs, particularly those from resistivity logs, match well with those from chemical analyses of produced water from East Mesa wells (Littleton and Burnett 1977). It should be pointed out that such log-derived salinity profiles also have applications in environmental impact considerations (Sanyal and Weiss 1977).

3. Sand counts obtained from well log interpretations proved to be the only means of well-to-well correlation of strata in East Mesa because conventional electrical log correlation is nearly impossible in this field. For example, Fig. 5.1 shows a vertical stratigraphic cross section developed from sand count profiles [averaged every 152.4 m (500 ft)] of some East Mesa wells. The complexity of sand development, particularly lenticularity, is evident from this figure. Such a definition of the reservoir is a necessity in any comprehensive reservoir engineering analysis.

Extensive use has also been made in Cerro Prieto of logs and logging data for correlation and structural interpretation. In particular, Tolivia M., (date unknown) used the SP curve and SARABAND logs to correlate the different strata and construct a model of the geothermal zone; Prian C. (1978) and Abril G. and Noble (1978) used both temperature and electrical logs in structural interpretations.

Fig. 5.1

SAND DISTRIBUTION

(From TRW Systems Group 1976a)

4. Log analysis provided the only practical means of estimating porosity values for developing porosity profiles in the East Mesa reservoir. It is impractical to derive porosity profiles from cores because of operational difficulties and excessive cost. Figures 5.2 through 5.4 (Bureau of Reclamation 1977) show the calculated porosity profiles. These profiles are useful in studying the geological characteristics of the reservoir and in providing quantitative input to reservoir engineering analysis.

5. Permeability values estimated from East Mesa logs, although less reliable than the computed porosity values, show fair agreement with permeabilities derived from well test analyses (Bureau of Reclamation 1977). It should be mentioned that log analysis was the only means of obtaining permeability profiles in these wells. Figures 5.5 through 5.7 (Bureau of Reclamation 1977) show the computed permeability profiles for the East Mesa area wells.

6. The net sand thicknesses estimated from well logs in East Mesa (H in Tables C-I through C-III) are indispensable in calculating average permeability (k) values from well tests, which yield a value for the product kH . The H values are also necessary to develop a quantitative model of the reservoir.

7. Although not specifically discussed in this report, interpretation of temperature logs, drill stem tests, mud logs, drill cutting logs and driller's logs have proved invaluable in making drilling and completion decisions in East Mesa and Cerro Prieto as in any other geothermal field. For

Fig. 5.2

(From Bureau of Reclamation 1977)

Fig. 5.3

(From Bureau of Reclamation 1977)

Fig. 5.4

(From Bureau of Reclamation 1977)

Fig. 5.5

(From Bureau of Reclamation 1977)

Fig. 5.6

(From Bureau of Reclamation 1977)

Fig. 5.7

(From Bureau of Reclamation. 1977)

example, proper interpretation of the temperature logs provides the static temperature profiles in the formation around the wellbore. These profiles have been helpful in making decisions about cementing, casing, liners, and perforating. Such profiles are also indispensable in any geological or engineering analysis of the reservoir. Drill stem tests have provided data on the reservoir water salinity and flow characteristics. Drill cuttings have proved very valuable in various geological and geochemical studies of the reservoir, as discussed in Section 4.3.

8. Various logs have proved helpful in the interpretation of geophysical data in East Mesa and Cerro Prieto as elsewhere. For example, density and acoustic logs have been useful in the interpretation of gravity and seismic surveys in East Mesa (Swanberg 1975). Temperature logs have been used extensively in the calculation of the heat flow characteristics of the reservoirs, particularly in East Mesa as described in TRW Systems Group (1976a), Black (1975), etc. SARA-BAND logs, salinity profiles from logs, and drill cutting data have provided important input in many geophysical, geochemical, and geological investigations of both fields, for example Swanberg (1975), Black (1975), Hoagland (1977), Randall (1976), Tolivia M. (date unknown).

5.2 Correlation of Log Interpretation with Other Reservoir Information

Structural Geology. The results of log interpretation by TRW Systems Group (1976a, 1976b) are summarized in Tables C-I through C-III. Figure 5.1 presents a sand distribution correlation in a section of the reservoir based on

the above mentioned results. Figures 5.2 through 5.4 present the calculated porosity profiles in various East Mesa wells (Bureau of Reclamation 1977). Figures 5.5 through 5.7 present the calculated profiles of permeability from the same wells (Bureau of Reclamation 1977). The above-mentioned figures and tables together with the dipmeter log interpretation (Figs. 4.2 and 4.3) and general geological information make possible the development of a structural model of the reservoir.

Because it is nearly impossible to identify marker beds and true formation tops in this field, developing true structural contour maps for the area is difficult. However, cross sections based on sand counts such as Fig. 5.1 reveal the essentially lenticular nature of the formations. The dipmeter data, sand count profiles, and seismic reflection data from this field indicate that the field lies in a southwest plunging anticlinal nose traversed by a NW-SE trending fault (Bureau of Reclamation 1977). In general, the dipmeter shows dip increasing with depth. Dipmeter data from the well 31-1 indicate a very abrupt change which implies a fault at 1704 m (5590 ft) (see Fig. 5.8, TRW Systems Group 1976a). This fault zone appears to be a shale on the well logs. This led TRW Systems Group (1976a) to speculate that this might be evidence for the fault zone having shale-like properties, that is, being impermeable.

A number of interference tests have been run in East Mesa wells. (The results of some of these tests are summarized in Table C-V.) These tests provide some information on the presence of faults and other boundaries in the reservoir. The tests indicate a single flow barrier between wells 31-1 and 38-30, possibly a sealing fault. This fault has been interpreted to be the same fault found in well 31-1 at 1704 m (5590 ft) according to the dipmeter data (TRW Systems Group 1976a).

DIPMETER DATA: MESA 31-1
(From TRW Systems Group 1976a)
Fig. 5.8

Two well interference tests were run in Cerro Prieto in 1978 (Schroeder et al. 1978). Although the results of these tests are considered to be preliminary, it should be noted that analysis of the data yielded much higher estimates of permeability than had been obtained previously.

TRW Systems Group (1976a) also inferred from a comparison of the dipmeter in Mesa 31-1 and correlation to East Mesa 38-30 that there is a rollover into the upthrown side of the fault, the dip in well 31-1 being westerly while in well 38-30 it is easterly. The structural interpretation also points out a flattening of the nose of the structure immediately northeast of the fault and, as TRW Systems Group (1976a) points out, this flattening coincides generally with an irregularity in the heat flow distribution.

Figure 5.9 (TRW Systems Group 1976a) is an example of an East Mesa area structural map drawn on the 1829-m (6000-ft) horizon in the Mesa 6-2 well. Three such maps were presented in TRW Systems Group (1976a) and were drawn on arbitrary structural surfaces picked from well logs at various depths because of the lack of definite formation tops in the East Mesa wells. The arbitrary surfaces were chosen near the approximate tops, midpoint, and bottom of the reservoir in well 6-2. Likewise, Fig. 5.10 (TRW Systems Group 1976a) is an example of an isopach drawn on the interval between the approximate horizons at 1220 m (4000 ft) and 1829 m (6000 ft).

Petrophysical Properties. There are three primary sources of data on the petrophysical properties of a reservoir; well logs, core analyses, and well tests. Core analysis data are limited because of the expense involved in obtaining the core and performing the analysis. Well test analysis provides reservoir properties averaged over a large volume

Fig. 5.9

(From TRW Systems Group 1976a)

Fig. 5.10

(From TRW Systems Group 1976a)

and therefore is not detailed. Well log analysis, then, is the prime means of obtaining detailed data from the reservoir. The evaluation of porosity and permeability of the East Mesa reservoir from well logs has been discussed in Section 4.3. Figures 5.2 through 5.4 show the calculated porosity profiles in several of the wells. As expected in any sedimentary sequence, porosity in East Mesa declines with depth. However, this decline is not uniform throughout the vertical extent of the reservoir and some sections show relatively constant porosity. Permeability profiles (Figs. 5.5 through 5.7) also show similar characteristics. The porosities and permeabilities in East Mesa are high as compared to most geothermal fields. The minimum porosity and permeability observed in the wells are approximately 10% and 10 millidarcies, respectively. In general, the porosity in the East Mesa reservoir is intergranular; however, a fracture zone is suspected near the bottom of well 6-1.

The petrophysical and structural interpretations from well logs in East Mesa match reasonably well with the results of well tests. In the earlier part of this section (5.2) there was a discussion of the agreement between the locations of faults as inferred from log data and from well tests. In Republic Geothermal well 38-30, the product of permeability (k) and net sand (h), kh , is 13 411 md-m as calculated from logs and 12 710 md-m as calculated from a buildup test (Narasimhan et al. 1977). Similarly, in Republic Geothermal well 16-19, the log-derived and buildup-derived kh values are 9114 and 10 577 md-m, respectively. However, most kh values calculated from well logs in East Mesa are somewhat higher than those calculated from well tests. This point has been discussed in Section 4.1. Table C-V is a summary of the results of the well tests on five Bureau of Reclamation wells (TRW Systems Group 1976a). Notice that the calculated permeabilities listed in this

table are higher than the corresponding summaries given in the zone summaries (Tables C-I through C-III).

Fluid and Heat Flow Characteristics. As pointed out in the first part of Section 5.2, the East Mesa reservoir is composed of a porous, permeable, lenticular sand-shale sequence associated with a plunging structure and is intersected by at least one major fault. Figure 5.11 is a comparison of the temperature profiles of two East Mesa wells with those from other areas of the Salton Trough. As can be seen in this figure, the change from a primarily conductive gradient to a primarily convective gradient occurs just above 914 m (3000 ft). This indicates that the reservoir top is at that level. However, no indication of a caprock down to 914 m (3000 ft) can be seen on the logs. The density log does not indicate any densified caprock layer as exists in the Dunes anomaly in the Imperial Valley. Instead, the function of the caprock in this reservoir is served by the innumerable shaly layers down to about 914 m (3000 ft) that effectively prevent any vertical movement of fluids. It is interesting to note that the salinity reversal also takes place at about the depth where the conductive gradient changes to a convective gradient. The significance of this is not well understood but may be connected with the fact that vertical flow is far more restricted above that depth than below.

Black (1975) attempted to prepare salinity cross-sections (for an example, see Fig. 5.12) from the log-derived salinity profiles in East Mesa wells. It was concluded on the basis of these sections that hot, saline water probably upwells near Mesa 6-1 and 6-2, spreads laterally, merges with the regional northwesterly water flow, and percolates downward near Mesa 8-1, 5-1, and 31-1 because of increased density.

(From Electrical Power Research Institute 1976)

Fig. 5.11

Fig. 5.12

The lateral boundaries of the reservoir are defined by the 149°C (300°F) isotherm, which is considered to be the lowest temperature for commercial exploitation of the water. The bottom of the reservoir can be taken either as the depth below which porosity and permeability are too low for commercial production or the maximum economical drilling depth, whichever is shallower. In the East Mesa reservoir, in most wells, permeability drops to as low as 10 millidarcies (which is a possible economic limit of productive capacity), near the 2438-m (8000-ft) level. In general, shaliness increases and, correspondingly, porosity and permeability decrease rapidly at depths below 2134-m (7000-ft). Thus, the effective reservoir bottom lies somewhere between 2134 m (7000-ft) and 2438-m (8000-ft). Figure 5.13 shows the isotherms, as determined from temperature logs, for East Mesa at the 1829-m (6000-ft) level. The area enclosed by the 149°C (300°F) contour may be considered the areal extent of the reservoir near its bottom, while the 149°C (300°F) isotherm at the 914-m (3000-ft) level can be taken as the boundary at the reservoir top. It should be noted that the four older, abandoned wells do not have commercial temperatures but do have higher porosities and permeabilities. It has been speculated that this may be due to the fact that the high temperature of geothermal water has reduced porosities in the central part of the reservoir (TRW Systems Group 1976a).

Summary of Reservoir Characteristics. Based on log analysis supplemented by well tests, coring and geological/geochemical/geophysical data, one can summarize the characteristics of the East Mesa reservoir as follows. The East Mesa geothermal reservoir lies on a southwest plunging structural nose traversed by faulting. It is considered to be bounded

FIG. 5.13

(From TRW Systems Group 1976a)

by the 149°C (300°F) isotherm with the top being at about 914 m (3000 ft) and bottom (as restricted by low porosity and permeability) somewhere between 2134 and 2438 m (7000 and 8000 ft). The horizontal cross section of the reservoir (as limited by the 149°C (300°F) isotherm) is roughly elliptical and covers an area of approximately 32 km² (12.5 sq miles). The reservoir is a lenticular sand/shale sequence with porosity and permeability decreasing with depth. Temperature in the reservoir ranges from 149°C (300°F) to almost 193°C (380°F). Salinity of the water in the reservoir varies, with an average being about 5000 ppm total dissolved solids. The reservoir is overlain by several hundred meters of sediments containing many shaly intervals that prevent any vertical fluid movement. This sedimentary layer has a conductive temperature profile while within the reservoir itself, the vertical temperature profile is nearly convective. In the horizontal direction, temperatures decrease away from the center of the reservoir, which appears to be in the area of wells 44-7, 6-1 and 6-2.

TRW Systems (1976a) estimates that the reservoir contains $2.6 \times 10^9 \text{ m}^3$ (6.9×10^{11} gallons) of water. The thermal content of this water is estimated to be $2.27 \times 10^{17} \text{ J}$ ($2.15 \times 10^{15} \text{ Btu}$), while the heat content of the porous reservoir rock matrix is about $2.79 \times 10^{18} \text{ J}$ ($2.65 \times 10^{15} \text{ Btu}$). The total heat content of the reservoir, rock and water (neglecting heat contained in clay and shales) is $5.06 \times 10^{18} \text{ J}$ ($4.8 \times 10^{15} \text{ Btu}$).

6. CONCLUSIONS

The primary conclusion that can be drawn from this study is that despite current deficiencies in technology, logs and log interpretation are definitely a great aid in

almost all phases of geothermal exploration and development. Logs provide more detailed information about reservoir characteristics than other available data sources, such as core data and well tests. This is particularly true since core data from geothermal wells are scarce.

Logs and log interpretation have been particularly useful in the structural mapping of the reservoirs in Cerro Prieto and East Mesa where structural correlations are very difficult. They have also been very useful in the computation of salinities and the creation of salinity profiles. Log analysis has also provided the only feasible means of obtaining continuous porosity and permeability profiles in geothermal wells. This work is helpful in predictions of production and performance.

There are obviously many improvements that are needed in both logging equipment and in log analysis techniques. The heat limitation on down hole logging equipment is still a serious problem in the higher temperature reservoirs such as Cerro Prieto. The ability to obtain good quality logs under adverse environmental conditions is essential to developing better interpretation methods. Much work still needs to be done to improve the quality of log analysis in geothermal wells. One particular area that needs additional effort is the accurate determination of formation temperatures at the time logs are run and the study of temperature effects on logging tool response. Considerable effort in this project was devoted to this area of study, and it is felt some significant contributions were made. Another prime area that needs more effort is mineral and rock identification and correlation with tool response characteristics for the formations that are encountered in geothermal logging. It is expected that some of the DOE programs currently under way will aid greatly in solving

some of the present problems with equipment and interpretation technology.

One difficulty encountered during this project, particularly with regard to Cerro Prieto, is the lack of available information. Either data cannot be located or the obtaining of the data is difficult and time-consuming. It is hoped that as the geothermal industry matures, the exchange of data will become more common and routine. Programs such as the Mexican-American cooperative program at Cerro Prieto, which is being coordinated by the Lawrence Berkeley Laboratory, should aid in making data more readily available.

APPENDIX A

WELL LOG LIST - EAST MESA

COMPANY

REPUBLIC GEOTHERMAL, INC.
WELL

WELL

EAST MESA 78-30

STATE

country

~~IMPERIAL~~

CALIFORNIA

FIELD

EAST MESA

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1. *Chlorophyll a* and *Chlorophyll b* were determined by the method of Arar and Collins (1971). The concentration of chlorophyll was expressed as $\mu\text{g mL}^{-1}$ of the sample.

100

Age Group	1970	1980	1990	2000	2010	2020
0-14	25	22	18	15	12	10
15-24	18	16	14	12	10	8
25-34	12	10	8	6	4	3
35-44	8	7	6	5	4	3
45-54	5	4	3	2	1	1
55-64	3	2	1	1	1	1
65-74	2	2	2	2	2	2
75+	5	6	7	8	12	25

COMPANY

WELL

FIELD

EAST MESA

STATE
II

COUNTRY
CALIFORNIA

109

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COMPANY

REPUBLIC GEOTHERMAL, INC.

WELL

EAST MESA 18-28

FIELD

EAST MESA

STATE

IMPERIAL

COUNTRY

CALIFORNIA

[illegible]

 	

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[illegible]

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1. The first group of variables includes the following:

- a. The number of years since the last election.
- b. The number of years since the last election.
- c. The number of years since the last election.
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- x. The number of years since the last election.
- y. The number of years since the last election.
- z. The number of years since the last election.

1

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FIELD

EAST MESA HOLTVILLE

10

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[illegible]

 
Graduate	~85	~15

2

MESA ANOMALY

10

CALIFORNIA

 

1. 2. 3. 4.

97

TESSA ANOMALY

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GEOTHERMAL WELL LOG CATALOG						COMPANY	UNITED STATES BUREAU OF RECLAMATION		WELL	STATE	COUNTRY	FIELD
								MESA 6-1	IMPERIAL	CALIFORNIA	MESA ANOMALY	
DATE	TYPE	LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING						
7/1/72	DUAL INDUCTION	LATEROLOG	1	S.W.S.	2500	378						
7/39/72	DUAL INDUCTION	- LATEROLOG	2	S.W.S.	7286	2505						
8/13/72	DUAL INDUCTION	- LATEROLOG	3	S.W.S.	8023	7292						
7/2/72	BOREHOLE COMPENSATED	SONIC LOG	1	S.W.S.	2495	378						
7/30/72	BOREHOLE COMPENSATED	SONIC LOG	2	S.W.S.	7280	2505						
8/14/72	BOREHOLE COMPENSATED	SONIC LOG	3	S.W.S.	8014	7292						
7/2/72	COMPENSATED NEUTRON-FORMATION	DENSITY	1	S.W.S.	2502	22						
7/30/72	COMPENSATED NEUTRON-FORMATION	DENSITY	2	S.W.S.	7394	8027						
8/14/72	COMPENSATED NEUTRON-FORMATION	DENSITY	3	S.W.S.	8027	7292						
7/30/72	TEMPERATURE	LOG	1	S.W.S.	4726	200						
	COMPUTER PROCESSED	INTERPRETATION-SARABAND	1	S.W.S.	2480	380						
	COMPUTER PROCESSED	INTERPRETATION-SARABAND	2	S.W.S.	7290	2508						
	COMPUTER PROCESSED	INTERPRETATION-SARABAND	3	S.W.S.	8000	7300						

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FIELD

MESA ANOMALY

COUNTRY

CALIFORNIA

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APPENDIX B

WELL LOG LIST - CERRO PRIETO

 

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CERRO PRIETO

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Age Group	Percentage of Respondents
18-29	85%
30-49	80%
50-69	75%
70+	70%

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CERRO PRIETO

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COMISION DE ENERGIA GEOTERMICA

COMISION DE ENERGIA GEOTERMICA

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CERRO PRIETO

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ERRO PRIETO

[illegible]

1. *Chlorophyll a* (Chl *a*)

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 104. *Chlorophyll ayz* (Chl *ayz*)
 105. *Chlorophyll ayz* (Chl *ayz*)
 106. *Chlorophyll azz* (Chl *azz*)
 107. *Chlorophyll azaa* (Chl *aza*)
 108. *Chlorophyll abz* (Chl *abz*)
 109. *Chlorophyll acz* (Chl *acz*)
 110. *Chlorophyll adz* (Chl *adz*)
 111. *Chlorophyll aez* (Chl *aez*)
 112. *Chlorophyll afz* (Chl *afz*)
 113. *Chlorophyll agz* (Chl *agz*)
 114. *Chlorophyll ahz* (Chl *ahz*)
 115. *Chlorophyll aiz* (Chl *aiz*)
 116. *Chlorophyll ajz* (Chl *ajz*)
 117. *Chlorophyll akz* (Chl *akz*)
 118. *Chlorophyll alz* (Chl *alz*)
 119. *Chlorophyll amz* (Chl *amz*)
 120. *Chlorophyll anz* (Chl *anz*)
 121. *Chlorophyll aoz* (Chl *aoz*)
 122. *Chlorophyll apz* (Chl *apz*)
 123. *Chlorophyll aqz* (Chl *aqz*)
 124. *Chlorophyll arz* (Chl *arz*)
 125. *Chlorophyll asz* (Chl *asz*)
 126. *Chlorophyll atz* (Chl *atz*)
 127. *Chlorophyll auz* (Chl *auz*)
 128. *Chlorophyll avz* (Chl *avz*)
 129. *Chlorophyll awz* (Chl *awz*)
 130. *Chlorophyll axz* (Chl *axz*)
 131. *Chlorophyll ayz* (Chl *ayz*)
 132. *Chlorophyll ayz* (Chl *ayz*)
 133.

1. The first step in the process is to identify the problem or issue that needs to be addressed. This involves gathering information and understanding the context of the problem.

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FIELD

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COMPANY

COMISION DE ENERGIA GEOTERMICA

WELL

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FIELD

CERRO PRIETO

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BAJA CALIFORNIA

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131

COMISION DE ENERGIA GEOTERMICA

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CERRO PRIETO

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FIELD
CERRO PRIETO

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122. *Chlorophyll apz* (Chl *apz*)
123. *Chlorophyll aqz* (Chl *aqz*)
124. *Chlorophyll arz* (Chl *arz*)
125. *Chlorophyll asz* (Chl *asz*)
126. *Chlorophyll atz* (Chl *atz*)
127. *Chlorophyll auz* (Chl *auz*)
128. *Chlorophyll avz* (Chl *avz*)
129. *Chlorophyll awz* (Chl *awz*)
130. *Chlorophyll axz* (Chl *axz*)
131. *Chlorophyll ayz* (Chl *ayz*)
132. *Chlorophyll ayz* (Chl *ayz*)
133. *Chlorophyll azz* (Chl *azz*)
134. *Chlorophyll azaa* (Chl *aza*)
135. *Chlorophyll abz* (Chl *abz*)
136. *Chlorophyll acz* (Chl *acz*)
137. *Chlorophyll adz* (Chl *adz*)
138. *Chlorophyll aez* (Chl *aez*)
139. *Chlorophyll afz* (Chl *afz*)
140. *Chlorophyll agz* (Chl *agz*)
141. *Chlorophyll ahz* (Chl *ahz*)
142. *Chlorophyll aiz* (Chl *aiz*)
143. *Chlorophyll ajz* (Chl *ajz*)
144. *Chlorophyll akz* (Chl *akz*)
145. *Chlorophyll alz* (Chl *alz*)
146. *Chlorophyll amz* (Chl

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MICRO SURVEY (2"/5")

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FIELD
CERRO PRIETO

 

COUNTRY

MEXICO

[illegible]

GEOTHERMAL WELL LOG CATALOG

COMPANY						WELL		FIELD	
COMISION DE ENERGIA GEOTERMICA						M-30		CERRO PRIETO	
STATE						COUNTRY			
BAJA CALIFORNIA						MEXICO			
DATE	TYPE LOG		RUN NO.	LOG COMPANY	LOWER READING	UPPER READING			
8/21/72	ELECTRICAL (2")		1	S.W.S.	2326	507			
8/21/72	ELECTRICAL (5")		1	S.W.S.	2326	507			
9/22/72	DUAL INDUCTION - LATEROLOG (2")		2	S.W.S.	4918	2293			
9/22/72	DUAL INDUCTION - LATEROLOG (5")		2	S.W.S.	4918	2293			
8/21/72	COMPENSATED FORMATION DENSITY (2")		1	S.W.S.	2325	508			
8/21/72	COMPENSATED FORMATION DENSITY - G.G. (5")		1	S.W.S.	2325	508			
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1. *What is the main purpose of this document?*
 2. *What are the key findings of the study?*
 3. *What are the implications of these findings for practice?*
 4. *What are the limitations of the study?*
 5. *What are the conclusions of the study?*

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P.G.A.C

P.G.A.C

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CERRO PRIETO

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COMISION DE ENERGIA GEOTERMICA

M-45

FIELD
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BAJA CALIFORNIA

COUNTRY

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CERRO PRIETO

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STATE
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country

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FIELD

CERRO PRIETO

COUNTRY

MEXICO

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COMPANY

COMPANY

COMISION FEDERAL DE ELECTRICIDAD

WELL

M-91

STATE

BAJA CALIFORNIA

COUNTRY

MEXICO

FIELD

CERRO PRIETO

[illegible]

<p> 1. 1990年12月31日以前，在北京市行政区域内，从事生产、经营活动的个体工商户，其经营期限满5年的，应当依法办理换照手续。 </p>	<p> 2. 1990年12月31日以前，在北京市行政区域内，从事生产、经营活动的个体工商户，其经营期限满5年的，应当依法办理换照手续。 </p>
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CERRO PRIETO

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APPENDIX C

TABULAR DATA - EAST MESA AREA WELLS

TABLE C-I

ZONE SUMMARIES: BUREAU OF RECLAMATION
EAST MESA WELLS

(From TRW Systems Group 1976a)

Interval (ft)	Mesa 6-1				Mesa 6-2				Mesa 8-1				Mesa 5-1				Mesa 31-1			
	H	Ø	K _h	K _v	H	Ø	K _h	K _v	H	Ø	K _h	K _v	H	Ø	K _h	K _v	H	Ø	K _h	K _v
1001-1250	---	--	---	---	15	36	1469	785	---	--	---	---	---	--	---	---	---	--	---	---
1251-1500	---	--	---	---	29	35	1582	602	---	--	---	---	124	34	927	429	88	32	493	230
1501-1750	---	--	---	---	91	35	1073	519	25	32	676	207	114	33	631	292	137	32	471	206
1751-2000	---	--	---	---	121	34	997	438	106	31	493	187	124	35	1379	552	81	33	805	357
2001-2250	---	--	---	---	114	33	608	266	94	32	871	247	179	34	877	412	146	31	431	185
2251-2500	---	--	---	---	138	32	642	261	188	30	437	135	161	32	470	232	112	32	880	226
2501-2750	173	30	326	112	139	32	461	208	169	29	250	95	204	31	383	183	118	32	699	233
2751-3000	136	26	154	43	196	31	400	183	170	29	363	100	164	30	227	122	191	31	403	163
3001-3250	146	24	62	25	129	28	182	79	168	24	69	24	156	29	165	84	149	29	178	90
3251-3500	130	23	65	18	165	29	275	98	157	23	71	15	140	25	62	33	158	28	142	62
3501-3750	123	19	20	6	138	25	148	29	133	16	3	2	162	26	88	37	130	28	171	80
3751-4000	166	28	282	69	85	22	37	11	143	17	9	3	202	25	63	26	55	29	215	85
4001-4250	155	24	177	23	148	28	249	64	203	21	35	9	167	25	74	28	192	28	148	65

H = Net sand thickness (feet)

Ø = Average porosity (percent)

K_h = Average horizontal permeability (millidarcies)K_v = Average vertical permeability (millidarcies)

TABLE C-I (cont'd)
 ZONE SUMMARIES: BUREAU OF RECLAMATION
 EAST MESA WELLS (cont'd)

(From TRW Systems Group 1976a)

Interval (ft)	Mesa 6-1				Mesa 6-2				Mesa 8-1				Mesa 5-1				Mesa 31-1			
	H	Ø	K _h	K _v	H	Ø	K _v	K _v	H	Ø	K _h	K _v	H	Ø	K _h	K _v	H	Ø	K _h	K _v
4251-4500	184	26	321	35	172	26	96	34	152	18	22	4	199	22	30	13	184	27	97	51
4501-4750	195	25	373	30	184	26	280	35	183	24	57	23	196	25	74	27	133	26	74	38
4751-5000	187	29	649	86	170	27	198	54	180	19	18	6	140	26	80	35	175	27	110	52
5001-5250	147	22	328	14	144	20	21	7	190	19	11	5	156	24	57	24	151	26	69	34
5251-5500	192	24	160	24	172	20	27	6	136	17	8	3	168	23	37	16	175	25	60	29
5501-5750	194	24	59	20	142	23	36	14	156	13	14	4	184	24	49	22	155	24	55	20
5751-6000	137	24	44	21	---	---	---	---	198	22	30	13	212	24	53	24	138	25	117	29
6001-6250	183	23	42	17	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
6251-6500	139	20	25	7	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
6501-6750	82	22	27	11	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
6751-7000	148	28	197	65	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
7001-7250	98	26	91	40	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
7251-7500	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

H = Net sand thickness (feet)
 Ø = Average porosity (percent)
 K_h = Average horizontal permeability (millidarcies)
 K_v = Average vertical permeability (millidarcies)

TABLE C-II

ZONE SUMMARIES: REPUBLIC GEOTHERMAL
EAST MESA WELLS

(From TRW Systems Group 1976a)

Interval (ft)	Republic 38-30				Republic 16-29				Republic 18-28			
	H	Ø	K _h	K _v	H	Ø	K _h	K _v	H	Ø	K _h	K _v
1501-1750	223	34	1023	460	---	---	---	---	---	---	---	---
1751-2000	140	32	756	286	---	---	---	---	---	---	---	---
2001-2250	155	34	1064	439	---	---	---	---	---	---	---	---
2251-2500	166	31	573	205	---	---	---	---	---	---	---	---
2501-2750	161	31	467	166	---	---	---	---	---	---	---	---
2751-3000	214	36	1645	772	---	---	---	---	---	---	---	---
3001-3250	214	33	879	331	---	---	---	---	---	---	---	---
3251-3500	171	28	149	70	---	---	---	---	---	---	---	---
3501-3750	181	29	322	91	---	---	---	---	---	---	---	---
3751-4000	166	31	473	159	---	---	---	---	---	---	---	---
4001-4250	111	31	714	184	---	---	---	---	---	---	---	---
4251-4500	145	30	265	101	---	---	---	---	---	---	---	---
4501-4750	195	30	432	123	---	---	---	---	---	---	---	---
4751-5000	189	28	367	78	175	26	190	39	---	---	---	---
5001-5250	---	---	---	---	182	25	130	31	---	---	---	---

H = Net sand thickness (feet)
 Ø = Average porosity (percent)
 K_h = Average horizontal permeability (millidarcies)
 K_v = Average vertical permeability (millidarcies)

TABLE C-III
 ZONE SUMMARIES: ABANDONED HOLES
 EAST MESA AREA

(From TRW Systems Group 1976a)

Interval (ft)	Shafter Barbara				Texaco Ingebretsen				Magma Sharp				Am.Petrofina #27-1			
	H	Ø	K _h	K _v	H	Ø	K _h	K _v	H	Ø	K _h	K _v	H	Ø	K _h	K _v
6001 - 6250	151	36	2128	711	103	36	1490	680	---	---	---	---	53	33	690	305
6251 - 6500	141	36	1928	733	129	30	605	119	---	---	---	---	135	33	903	341
6501 - 6750	209	22	96	11	158	29	592	95	---	---	---	---	158	32	725	205
6751 - 7000	156	30	331	132	27	36	1633	678	---	---	---	---	86	31	466	158
7001 - 7250	148	27	96	47	105	30	550	112	---	---	---	---	138	29	278	105
7251 - 7500	220	15	56	1.5	134	28	225	69	---	---	---	---	33	28	374	73
7501 - 7750	167	10	0.4	0.4	123	28	234	72	---	---	---	---	94	27	208	45
7751 - 8000	159	12	0.9	0.7	112	30	370	120	---	---	---	---	128	26	87	35
8001 - 8250	---	---	---	---	201	25	125	25	---	---	---	---	66	22	24	11
8251 - 8500	---	---	---	---	139	25	117	31	---	---	---	---	110	21	80	10
8501 - 8750	---	---	---	---	112	23	89	14	---	---	---	---	30	18	69	3.7
8751 - 9000	---	---	---	---	134	29	360	83	---	---	---	---	122	19	13	4.6
9001 - 9250	---	---	---	---	104	29	363	103	---	---	---	---	112	21	75	9
9251 - 9500	---	---	---	---	187	25	135	25	---	---	---	---	101	27	262	46
9501 - 975	---	---	---	---	208	26	78	37	---	---	---	---	209	21	85	9
9751 -10000	---	---	---	---	194	23	37	15	---	---	---	---	204	16	8	1.8
10001-10250	---	---	---	---	212	22	32	13	---	---	---	---	---	---	---	---
10250-10500	---	---	---	---	150	21	30	8	---	---	---	---	---	---	---	---
10501-10750	---	---	---	---	99	22	45	13	---	---	---	---	---	---	---	---
10751-11000	---	---	---	---	130	21	33	9	---	---	---	---	---	---	---	---
11001-11250	---	---	---	---	160	19	10	5	---	---	---	---	---	---	---	---
11251-11420	---	---	---	---	93	17	6	3	---	---	---	---	---	---	---	---

N = Net sand thickness (feet)
 Ø = Average porosity (percent)

K_h = Average horizontal permeability (millidarcies)
 K_v = Average vertical permeability (millidarcies)

TABLE C-IV

CORE ANALYSIS SUMMARY - EAST MESA
(From TRW Systems Group 1976a)

Depth (ft)	Porosity (%)	Permeability (md)		Grain Density
		Horizontal	Vertical	
EAST MESA:				
<u>Mesa 5-1</u>				
5598.4	27.2	61	41	2.64
5599.6	28.0	67	36	2.66
5600.4	28.0	92	77	2.66
5601.2	27.5	90	26	2.65
5601.8	25.9	16	6.4	2.67
5602.5	27.0	26	11	2.65
5603.3	29.4	120	68	2.65
5604.3	12.7	3.2	14	2.67
5618.3	25.7	45	37	2.68
5619.4	21.3	49	23	2.66
5620.6	25.7	95	315	2.67
5621.6	29.4	65	57	2.65
5622.7	29.2	215	250	2.66
5623.4	27.0	125	185	2.63
5624.3	29.6	285	460	2.66
5624.7	25.2	23	6.4	2.69
5625.7	25.2	70	5.7	2.66
5626.6	28.0	150	105	2.63
5627.8	22.1	31	28	2.70
5628.6	6.2	0.06	0.07	2.67
5634.3	8.3	0.08	0.08	2.72
5635.2	25.2	31	19	2.64
<u>Mesa 6-1</u>				
2548-2603	24.1	--	<0.1	2.75
2548-2603	24.3	--	<0.1	2.73
4432-4480	5.8	0.2	<0.1	2.70
4432-4480	35.9	791	--	2.66
4449-4450	10.6	0.53	0.40	2.695
4456-4457	15.5	5.8	1.3	2.719
6988-7045	4.6	0.1	<0.1	2.71
6988-7045	11.1	<0.1	--	2.76
7007-7008	17.2	0.033	0.011	2.843
7009-7010	20.2	0.28	0.11	2.840

TABLE C-IV (cont'd)

CORE ANALYSIS SUMMARY - EAST MESA

(From TRW Systems Group 1976a)

Depth (ft)	Porosity (%)	Permeability (md)		Grain Density
		Horizontal	Vertical	
<u>Mesa 8-1</u>				
5800.3	24.3	192	222	2.65
5801.0	25.6	272	432	2.65
5804.8	15.6	8.85	6.4	2.66
5808.1	12.9	0.65	0.2	2.67
5826.9	18.9	12.5	1.8	2.66
<u>Mesa 31-1</u>				
5644.6	7.8	<0.1	<0.1	2.67

TABLE C-V

WELL TEST SUMMARY

(From TRW Systems Group 1976a)

Well	Date	Test	Elapsed Time	Transmissivity (md. - ft)	Producing Interval (ft)	Approximate Permeability (md.)	Notes
Mesa 31-1	7/21/75	Drawdown	329 min	22,200	755	30	Sealing boundary present
		Recovery	284 min	22,200	755	30	
Mesa 31-1	7/30/75	Recovery	690 min.	29,800	755	40	
Mesa 5-1	1/8/75	Drawdown	600 min	5,700	1000	6	
Mesa 8-1	4/21/75	Drawdown	340 min	13,500	1056	13	
		Recovery	300 min	13,500	1056	13	
Mesa 6-1	12/28/72	Recovery	16 days	296	641	0.5	
Mesa 6-1	1/24/73	Recovery	147 min	296	641	0.5	
Mesa 6-2 producing Mesa 6-1 observing Mesa 8-1 observing	—	Interference	Approx. 10 days	11,200 No Response	—	10-20	Leaky boundary present
Mesa 6-2 producing Mesa 8-1 observing	—	Interference	Approx. 3 weeks	No Response			
Mesa 31-1 producing Republic 38-30 observing	—	Interference	Approx. 10 days	29,500		20-40	Sealing boundary present

Interference test data: After LBL.

APPENDIX D

COMPUTER LISTINGS OF TEMPERATURE PROFILE AND HEAT FLOW CALCULATIONS

TABLE D-I

LOGCALC RESULTS
 WELL NUMBER 22001 TOP OF INTERVAL (TOPD) = 2491.00 02/21/79 09 09 57
 BOTTOM OF INTERVAL (BOTD) = 2530.00

HOLE DEPTH (FEET) -DEPTH -	TEMP. HOLE AT TIME 0 (DEG. C) -T0WC -	TEMP. HOLE AT TIME 1 (DEG. C) -T1WC -	TEMP. HOLE AT TIME 2 (DEG. C) -T2WC -	TEMP. FORM. (INITIAL) (DEG. C) -TFC -	HOLE DIAMETER (INCHES) -CAL -	INVASION DIAMETER (INCHES) -DI -	95 PCT TEMP CHANGE DIAM. (INCHES) -DT95 -	TEMPERATURE CHANGE DIAM. (INCHES) -DT -	HOLE DEPTH (FEET) -DEPTH -
2491.	100.2	104.8	119.5	143.2	10.9	33.1	103.1	245.4	2491.
2492.	100.2	104.8	119.5	143.2	11.0	35.7	103.1	245.4	2492.
2493.	100.2	104.8	119.5	143.3	11.2	34.4	103.1	245.3	2493.
2494.	100.2	104.8	119.5	143.3	11.2	34.9	103.1	245.3	2494.
2495.	100.2	104.8	119.5	143.3	11.2	34.6	103.1	245.3	2495.
2496.	100.2	104.8	119.5	143.3	11.4	34.8	103.1	245.2	2496.
2497.	100.2	104.8	119.5	143.3	11.5	37.8	103.0	245.2	2497.
2498.	100.2	104.8	119.5	143.3	11.0	37.7	103.0	245.2	2498.
2499.	100.2	104.8	119.5	143.3	11.1	36.0	103.0	245.2	2499.
2500.	100.2	104.8	119.5	143.3	11.1	34.4	103.0	245.1	2500.
2501.	100.2	104.8	119.5	143.3	11.6	37.1	103.0	245.1	2501.
2502.	100.2	104.8	119.5	143.3	11.6	35.8	103.0	245.1	2502.
2503.	100.2	104.8	119.5	143.3	11.5	39.4	103.0	245.1	2503.
2504.	100.2	104.8	119.5	143.2	11.5	40.7	103.0	245.0	2504.
2505.	100.2	104.8	119.5	143.2	11.1	38.2	103.0	245.0	2505.
2506.	100.2	104.8	119.4	143.2	11.1	36.3	103.0	245.0	2506.
2507.	100.2	104.8	119.4	143.2	11.1	38.1	102.9	244.9	2507.
2508.	100.2	104.8	119.4	143.2	11.1	40.5	102.9	244.9	2508.
2509.	100.2	104.8	119.4	143.2	11.1	40.1	102.9	244.9	2509.
2510.	100.1	104.8	119.4	143.2	11.1	39.5	102.9	244.9	2510.
2511.	100.1	104.8	119.4	143.2	11.3	39.6	102.9	244.8	2511.
2512.	100.1	104.7	119.4	143.2	11.4	39.5	102.9	244.8	2512.
2513.	100.1	104.7	119.4	143.1	11.3	39.1	102.9	244.8	2513.
2514.	100.1	104.7	119.4	143.1	11.1	39.3	102.9	244.8	2514.
2515.	100.1	104.7	119.4	143.1	10.8	40.3	102.9	244.7	2515.
2516.	100.1	104.7	119.4	143.1	10.8	38.4	102.9	244.7	2516.
2517.	100.1	104.7	119.3	143.1	11.2	37.3	102.8	244.7	2517.
2518.	100.1	104.7	119.3	143.1	11.4	36.6	102.8	244.6	2518.
2519.	100.1	104.7	119.3	143.1	11.4	37.2	102.8	244.6	2519.
2520.	100.1	104.7	119.3	143.1	11.4	37.1	102.8	244.6	2520.
2521.	100.1	104.7	119.3	143.1	11.3	37.8	102.8	244.6	2521.
2522.	100.1	104.7	119.3	143.0	11.3	38.5	102.8	244.5	2522.
2523.	100.0	104.7	119.3	143.0	11.3	37.1	102.8	244.5	2523.
2524.	100.0	104.7	119.3	143.0	11.1	36.8	102.8	244.5	2524.
2525.	100.0	104.7	119.3	143.0	11.3	37.8	102.8	244.5	2525.
2526.	100.0	104.6	119.3	143.0	11.3	36.3	102.8	244.4	2526.
2527.	100.0	104.6	119.3	143.0	11.6	35.3	102.7	244.4	2527.
2528.	100.0	104.6	119.3	143.0	11.5	35.1	102.7	244.4	2528.
2529.	100.0	104.6	119.2	143.0	11.1	33.5	102.7	244.3	2529.
2530.	100.0	104.6	119.2	143.0	11.2	37.5	102.7	244.3	2530.

TABLE D-II

LOGCALC RESULTS									
WELL NUMBER 22001		TOP OF INTERVAL (TOD) = 2491.00				02/21/79 09 09 57			
		BOTTOM OF INTERVAL (BOTD) = 2530.00							
HOLE DEPTH	TEMP. FORM.	TEMP. FORM.	TEMP. FORM.	TEMP. FORM.	TEMP. FORM.	TEMP. FORM.	TEMP. FORM.	TEMP. FORM.	HOLE DEPTH
(FEET)	DIAM 25 IN.	DIAM 50 IN.	DIAM 75 IN.	DIAM 100 IN.	DIAM 150 IN.	DIAM 200 IN.	DIAM 250 IN.	(INITIAL)	
(DEG. C)	(DEG. C)	(DEG. C)	(DEG. C)	(DEG. C)	(DEG. C)	(DEG. C)	(DEG. C)	(DEG. C)	(FEET)
-DEPTH -	-T25C -	-T50C -	-T75C -	-T100C -	-T150C -	-T200C -	-T250C -	-TFC -	-DEPTH -
2491.	118.3	131.7	137.7	140.8	142.9	143.2	143.2	143.2	2491.
2492.	118.3	131.7	137.7	140.8	142.9	143.2	143.2	143.2	2492.
2493.	118.3	131.7	137.7	140.8	142.9	143.2	143.3	143.3	2493.
2494.	118.3	131.7	137.7	140.8	142.9	143.2	143.3	143.3	2494.
2495.	118.3	131.7	137.7	140.8	142.9	143.2	143.3	143.3	2495.
2496.	118.3	131.7	137.7	140.9	142.9	143.2	143.3	143.3	2496.
2497.	118.3	131.7	137.7	140.9	142.9	143.2	143.3	143.3	2497.
2498.	118.3	131.7	137.7	140.9	142.9	143.2	143.3	143.3	2498.
2499.	118.3	131.7	137.7	140.9	142.9	143.2	143.3	143.3	2499.
2500.	118.3	131.8	137.7	140.9	142.9	143.2	143.3	143.3	2500.
2501.	118.3	131.7	137.7	140.9	142.9	143.2	143.3	143.3	2501.
2502.	118.3	131.7	137.7	140.9	142.9	143.2	143.3	143.3	2502.
2503.	118.3	131.7	137.7	140.8	142.9	143.2	143.3	143.3	2503.
2504.	118.3	131.7	137.7	140.8	142.9	143.2	143.2	143.2	2504.
2505.	118.3	131.7	137.7	140.8	142.9	143.2	143.2	143.2	2505.
2506.	118.3	131.7	137.7	140.8	142.8	143.2	143.2	143.2	2506.
2507.	118.3	131.7	137.7	140.8	142.8	143.2	143.2	143.2	2507.
2508.	118.2	131.7	137.7	140.8	142.8	143.2	143.2	143.2	2508.
2509.	118.2	131.7	137.6	140.8	142.8	143.1	143.2	143.2	2509.
2510.	118.2	131.7	137.6	140.8	142.8	143.1	143.2	143.2	2510.
2511.	118.2	131.7	137.6	140.8	142.8	143.1	143.2	143.2	2511.
2512.	118.2	131.6	137.6	140.8	142.8	143.1	143.2	143.2	2512.
2513.	118.2	131.6	137.6	140.7	142.8	143.1	143.1	143.1	2513.
2514.	118.2	131.6	137.6	140.7	142.8	143.1	143.1	143.1	2514.
2515.	118.2	131.6	137.6	140.7	142.7	143.1	143.1	143.1	2515.
2516.	118.2	131.6	137.6	140.7	142.7	143.1	143.1	143.1	2516.
2517.	118.2	131.6	137.6	140.7	142.7	143.0	143.1	143.1	2517.
2518.	118.2	131.6	137.6	140.7	142.7	143.0	143.1	143.1	2518.
2519.	118.2	131.6	137.5	140.7	142.7	143.0	143.1	143.1	2519.
2520.	118.1	131.6	137.5	140.7	142.7	143.0	143.1	143.1	2520.
2521.	118.1	131.6	137.5	140.7	142.7	143.0	143.1	143.1	2521.
2522.	118.1	131.6	137.5	140.7	142.7	143.0	143.0	143.0	2522.
2523.	118.1	131.5	137.5	140.6	142.7	143.0	143.0	143.0	2523.
2524.	118.1	131.5	137.5	140.6	142.6	143.0	143.0	143.0	2524.
2525.	118.1	131.5	137.5	140.6	142.6	143.0	143.0	143.0	2525.
2526.	118.1	131.5	137.5	140.6	142.6	142.9	143.0	143.0	2526.
2527.	118.1	131.5	137.5	140.6	142.6	142.9	143.0	143.0	2527.
2528.	118.1	131.5	137.5	140.6	142.6	142.9	143.0	143.0	2528.
2529.	118.1	131.5	137.4	140.6	142.6	142.9	143.0	143.0	2529.
2530.	118.1	131.5	137.4	140.6	142.6	142.9	143.0	143.0	2530.

TABLE D-III

WELL NUMBER 22001

LOGCALC RESULTS
TOP OF INTERVAL (TOPD) = 2491.0002/21/79 09 09 57
BOTTOM OF INTERVAL (BOTD) = 2530.00

HOLE DEPTH (FEET) -DEPTH -	THERMAL CONDUCTIVITY (BTU/F-H-FT) -K -	HEAT FLOW RATE (BTU/HR) -QR -	VOLUMETRIC HEAT CAP. (BTU/F-FT3) -VHC -	EFFECTIVE POROSITY (PERCENT) -PHIE -	-PPM1 -	-PPM2 -	-PPM3 -	TEMP. FORM. (INITIAL) (DEG. F) -TF -	HOLE DEPTH (FEET) -DEPTH -
2491.	55.0	567.6	48.5	29.8	7512.	9577.	14554.	289.8	2491.
2492.	54.4	561.7	48.0	25.4	7974.	10022.	15235.	289.8	2492.
2493.	53.9	555.8	47.5	22.6	9117.	11418.	17380.	289.9	2493.
2494.	53.6	553.3	47.3	20.2	9075.	11202.	17045.	289.9	2494.
2495.	53.8	555.5	47.4	20.9	8662.	10681.	16240.	289.9	2495.
2496.	54.6	563.1	48.1	24.7	7487.	9287.	14099.	289.9	2496.
2497.	54.5	562.8	48.1	25.0	8244.	10262.	15592.	289.9	2497.
2498.	54.3	560.2	47.8	24.9	9314.	11724.	17837.	289.9	2498.
2499.	54.3	560.1	47.8	24.7	8624.	10828.	16457.	289.9	2499.
2500.	54.7	564.9	48.2	28.0	7715.	9762.	14817.	289.9	2500.
2501.	55.3	570.9	48.8	30.2	6698.	8402.	12731.	289.9	2501.
2502.	55.6	574.1	49.0	32.7	6566.	8305.	12579.	289.9	2502.
2503.	55.5	573.2	49.0	31.5	6670.	8399.	12721.	289.9	2503.
2504.	55.1	568.7	48.6	30.3	7603.	9592.	14542.	289.8	2504.
2505.	55.4	571.9	48.9	32.5	6572.	8360.	12654.	289.8	2505.
2506.	55.5	572.7	49.0	32.9	6147.	7829.	11842.	289.8	2506.
2507.	55.1	569.1	48.6	30.3	6695.	8474.	12822.	289.8	2507.
2508.	54.9	567.0	48.5	28.3	7372.	9275.	14042.	289.8	2508.
2509.	55.1	568.7	48.6	28.9	7288.	9167.	13874.	289.7	2509.
2510.	55.2	569.7	48.7	30.9	7822.	9928.	15034.	289.7	2510.
2511.	54.9	566.8	48.5	30.0	8805.	11188.	16960.	289.7	2511.
2512.	54.8	565.7	48.4	28.4	8729.	11017.	16695.	289.7	2512.
2513.	54.7	564.7	48.3	25.8	7817.	9726.	14715.	289.7	2513.
2514.	54.9	566.4	48.5	26.9	7394.	9243.	13973.	289.6	2514.
2515.	55.2	570.0	48.8	30.3	7210.	9137.	13808.	289.6	2515.
2516.	54.9	566.4	48.5	29.4	7822.	9942.	15033.	289.6	2516.
2517.	54.6	563.4	48.2	27.5	8237.	10394.	15720.	289.6	2517.
2518.	54.8	565.4	48.4	28.1	7635.	9607.	14515.	289.6	2518.
2519.	55.0	566.9	48.5	27.8	7036.	8794.	13271.	289.5	2519.
2520.	54.9	566.7	48.5	28.3	7430.	9348.	14112.	289.5	2520.
2521.	55.1	568.6	48.7	30.4	7532.	9556.	14426.	289.5	2521.
2522.	55.4	571.9	49.0	33.7	7373.	9418.	14211.	289.5	2522.
2523.	55.3	570.1	48.8	32.0	7297.	9278.	13995.	289.5	2523.
2524.	55.0	567.4	48.6	28.8	6900.	8695.	13104.	289.4	2524.
2525.	55.0	566.9	48.6	29.9	7287.	9227.	13911.	289.4	2525.
2526.	54.7	564.1	48.3	28.9	7717.	9779.	14746.	289.4	2526.
2527.	53.7	554.2	47.5	25.6	11137.	14185.	21483.	289.4	2527.
2528.	53.9	555.6	47.6	25.1	10181.	12910.	19522.	289.4	2528.
2529.	55.2	568.9	48.8	31.2	6811.	8683.	13069.	289.3	2529.
2530.	55.1	567.8	48.7	30.1	7456.	9482.	14280.	289.3	2530.

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