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Geothermal Well Log Interpretation

Midterm Report

University of California

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Geothermal Well Log Interpretation

Midterm Report

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GEOTHERMAL WELL LOG INTERPRETATION
MIDTERM REPORT

by

S. K. Sanyal, L. E. Wells, and R. E. Bickham

ABSTRACT

In this midterm report on geothermal well log interpretation, we have defined reservoir types according to fluid phase and temperature, lithology, geologic province, pore geometry, and salinity and fluid chemistry. Improvements are needed in lithology and porosity definition, fracture detection, and thermal evaluation for more accurate interpretation. Further efforts are directed toward improving diagnostic techniques for relating rock characteristics and log response, developing petrophysical models for geothermal systems, and developing thermal evaluation techniques.

The Geothermal Well Log Interpretation study and report has concentrated only on hydrothermal geothermal reservoirs. Other geothermal reservoirs (hot dry rock, geopressured, etc.) are not considered in this study.

TASK 1: REVIEW OF THE STATE OF THE ART

Introduction

In the petroleum industry, well logging is a well-developed discipline that has matured over five decades. Compared to this, geothermal well logging is a very new enterprise.

By and large, the current practice has been to use the same logging equipment and log interpretation techniques for geothermal wells as is used for petroleum wells. However, this approach has proven either inadequate or ineffective in most geothermal areas. The problems here are of two types: (1) those associated with logging equipment and operation, 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 in petroleum wells. In many geothermal wells, some of the standard well logs cannot be acquired because the well temperatures are higher than the maximum temperature for which the logging tools are designed.

Logging service companies are beginning to develop instrumentation and interpretation techniques for geothermal wells. For example, Schlumberger Well Services has been offering a geothermal version of their SARABAND (a Schlumberger trademark) interpretation technique for geothermal wells in the Imperial Valley of California and the Mexicali Valley of Mexico. Dresser Atlas Corporation has recently developed a log interpretation scheme for The Geysers dry steam field based on gamma-ray, neutron, compensated density, caliper, and temperature logs. Both of these companies and other service companies are also engaged in developing new instrumentation for logging geothermal wells. However both instrumentation and interpretation development by the logging industry have been inadequate compared to the needs of the geothermal industry.

The Department of Energy has established a geothermal logging instrumentation development program at the Sandia Laboratories in New Mexico. The U.S. Geological Survey also has a similar program of instrumentation development for geothermal logging. These programs are progressing well and there are indications that most of the hardware-related problems of geothermal well logging instrumentation will be resolved over the next few years.

CURRENT PROBLEMS IN GEOTHERMAL WELL LOGGING

This section consists of problems associated with geothermal logging. These problems (Sanyal and Meidav, 1977) are in the areas of logging objectives, operation, and interpretation.

Logging Objective:

The most important objective of petroleum well logging is the determination of porosity and hydrocarbon saturation. For this reason, the bulk of research activity in the petroleum logging industry has been confined to developing new and better tools and interpretation techniques for measuring porosity and hydrocarbon saturation. In the geothermal reservoirs there is no hydrocarbon saturation and the nature of porosity is usually substantially different from that in a petroleum reservoir. The majority of geothermal reservoirs have fracture rather than intergranular porosity while the vast majority of petroleum reservoirs have intergranular rather than the fracture porosity. The state of the art of detection and quantification of the characteristics of fractures is relatively undeveloped in the logging industry.

It is thus apparent that even in their basic objectives the petroleum and geothermal logging industries differ; a large part of the know-how of the petroleum logging industry is not transferable to the geothermal industry.

The fundamental differences in the objectives of the two logging industries arise from the fact that petroleum reservoirs are mostly of the intergranular type occurring in relatively soft, sedimentary rocks at temperatures less than 150°C (300°F) and with water saturation less than 100 percent while geothermal reservoirs are usually of the fracture type occurring in hard, igneous and metamorphic rocks at temperatures higher than 150°C (300°F) and with 100 percent water (and rarely, steam) saturation.

Assessments of reservoir lithology and permeability are endeavors common to both industries. Here again basic differences occur. The majority of the petroleum reservoirs are in sedimentary rocks while very few commercial geothermal reservoirs except in the Imperial Valley, California, are known to occur in sedimentary rocks. The permeability in geothermal reservoirs is largely controlled by fractures and faults. The preponderance of fracturing in geothermal reservoirs is due to the hard, brittle nature of igneous and metamorphic rocks and tectonic activity in geothermal areas. Even a sedimentary-type geothermal reservoir often undergoes profuse igneous intrusion, contact metamorphism and hydrothermal alteration resulting in a brittle, fractured state.

Some of the other important objectives of geothermal well logging, such as assessment of water quality, equilibrium formation temperature, thermal and elastic properties of the formation, etc., have drawn relatively little attention in the petroleum industry, again because of the fundamental differences in the objectives of the two industries.

Logging Operation:

Routine well logging instrumentation in the petroleum industry is capable of working in 177°C (350°F) temperature. However, the majority of geothermal reservoirs are at higher temperatures. Sometimes the wellbore can be cooled down to 177°C (350°F) by circulation of cooled fluids before logging. But this consumes precious rig time and can be hazardous for open holes. In the case of the dry steam reservoirs at The Geysers (California), lost circulation problem is severe and wells here are usually drilled with air and cooling the borehole by fluid circulation is impractical. Many reservoirs are simply too hot to be cooled down to 177°C (350°F).

High-temperature (up to 260°C or 500°F) logging cables are now available, but most logging tools are still not rated for such temperatures. Schlumberger Well Services has a series of high-temperature, high-pressure tools (known as HEL or Hostile Environment Logging tools) developed for deep, hot petroleum wells. Dresser Atlas Corporation has recently been successful in using their new high-temperature tools run on a special 5/16-inch single-conductor cable to log steam wells at The Geysers with temperatures of 260°C (500°F) (Ehring and others, 1978). Sandia Laboratories has developed a number of high-temperature logging tools, which are currently being tested. The U.S. Geological Survey has developed some high-temperature logging tools, of which the Borehole Televiewer has been tested successfully in many geothermal fields (S. Keys, 1978). However most of these high-temperature logging tools are still not commercially available or widely tested.

The logging tools commonly used in the geothermal industry have sharply reduced lives because of the high temperature and corrosivity of geothermal fluids, even if the tool is rated for the temperature encountered. Hence these logging tools are not tested and calibrated often enough at these extreme conditions. Frequent breakdowns and the loss of logging tools in the well are common in geothermal operations and the hazards of a hot, open hole and the cost of rig time often lead to a rushed logging operation, which, in turn, may cause operational problems such as a stuck tool or poor log quality.

Since geothermal logging is only a few years old, very few field engineers have substantial experience in geothermal logging. Hence some problems during logging and recording may go undetected.

Log Interpretation Problems:

There are several common problems with the quality of geothermal well logs, many of which are also common in the petroleum industry. Poor quality of some geothermal logs may be due to high logging speed, improper scaling or calibration, unusual cable stretching, rugosity of the borehole, etc. Some typical examples of such problems are:

1. Discrepancy in depth between logs from the same well;
2. Lack of repeatability;
3. Improper scale;
4. Unusually high porosity because of borehole well caving;
5. Negative porosity due to wrong assumption of lithology;
6. Featureless, wandering SP curve (due to stray currents) through a thick, tight section;
7. SP baseline shift;
8. Mutually inconsistent responses of logs in a suite;

9. Inconsistency in water resistivity calculated by various methods;
10. Inconsistent or incomplete job-specific data;
11. Discrepancy between log and core data.

Most of the above-mentioned problems are known in the petroleum industry and can usually be resolved. However, there are other types of problems associated with log quality that cannot be easily resolved. These are accurate records of times at which drilling stopped, circulation stopped, various logging tools reached the bottom, etc. and the corresponding values of measured temperature. Unless these data are given it is difficult to assess the formation temperature at the time of logging.

Another type of common problem in geothermal well log interpretation is the lack of calibration data. Well logs are calibrated and tested against known lithologies common in the petroleum reservoirs, such as sandstone and limestone. When an "unusual" rock type is encountered, the log response may appear strange. Some corrections may be necessary to such a log response.

For example, in the Los Alamos Scientific Laboratory's (LASL) Hot Dry Rock Project Well No. 2 in the Jemez Mountains, some zones show increase in bulk density without corresponding decrease in the sonic travel time. This can be explained by the fact that the mafic rocks encountered in these zones have higher electron densities than does the medium used to calibrate the density logging tool (West and others, 1975). In the same well a zone shows a decrease in sonic travel time corresponding to an increase in bulk density, but the apparent neutron log porosity seems to increase. This may be caused by the presence of a material with a high neutron capture cross section, possibly a mafic type of intrusion (West and others, 1975). Calibration data are not available to resolve this type of problem. "Unusual" responses of this type are possible from geothermal wells in unfamiliar lithology.

One of the basic problems in geothermal well log interpretation is coping with unfamiliar lithology. Standard calibration and interpretation charts for well log analysis were designed for typical petroleum reservoir lithology: sandstone, shale, limestone, dolomite, and anhydrite. In geothermal reservoirs one often encounters crystalline igneous and metamorphic rocks, vesicular volcanic rocks, glassy or crystalline volcanic rocks, volcanic ashes, and welded volcanic rock material. Lack of calibration data for such lithologies presents a problem in interpretation. Standard interpretation charts are often inadequate for geothermal reservoir lithology. For example, in the Raft River geothermal field, the points on bulk density-neutron porosity crossplots sometimes fall outside the range of standard charts.

Lack of complete log suites sometimes poses a problem in geothermal well log analysis. In the face of complex, unfamiliar and abruptly changing lithology, a three porosity logging suite is desirable and may be essential. A full log suite may not be run in all geothermal wells because of cost considerations or operational problems. This makes lithology identification and porosity evaluation difficult.

Most of the interpretation techniques and standard equations for well logs were developed for petroleum reservoirs and do not necessarily apply to geothermal reservoirs. For example, there is little validity in using such standard equations as Archie's Formula or the Humble Formula in a fractured volcanic geothermal reservoir. Some of the overlay and crossplot concepts do not apply well for geothermal reservoirs. Calculation of formation water resistivity from the SP or electrical resistivity logs from a geothermal well can be frustrating.

A very limited number of geothermal logs and core analysis reports are publicly available; a substantial data base of geothermal well logs is yet to be compiled.

As a result, empirical correlations (such as the Humble Formula in the petroleum industry) are yet to be developed for geothermal well log interpretation. Even for a specific reservoir, it is often difficult to develop a useful porosity-permeability transform from core data. This is usually due to the presence of fractures and abrupt changes in lithology.

Another problem to be remembered in analyzing geothermal well logs is that the present state of knowledge of the effects of high-temperature, pressure, and geothermal fluid chemistry on reservoir rocks is very primitive. For this reason use of core data to normalize well log data may not be justifiable in many geothermal situations. There is a great need for research in this area.

PUBLISHED INFORMATION ON INTERPRETATION

Case Histories:

Very little has been published on the techniques and case histories of geothermal log interpretation. The purpose of this section is to review the reported examples of geothermal log interpretation. In many ways the problems of geothermal well log analysis are the problems of analyzing unfamiliar lithologies. Examples of log analysis in unfamiliar lithologies have been reported from the mining industry and only rarely from the petroleum or geothermal industries. For the purposes of this report such unfamiliar lithologies as coal and evaporites will not be considered; these rock types are uncommon in the U.S. geothermal reservoirs.

Khatchikian and Lesta (1973) presented a paper on log interpretation for tuffites and tuffaceous sandstone formations from southern Argentina. Tuff has been encountered in several geothermal and oil reservoirs, but very little is known about its physical properties, which vary over a wide range, depending among other factors upon the environment and conditions under which it was deposited. Log responses for water-bearing tuff and oil-bearing sandstone are very similar, especially when the formation water is relatively fresh. They constructed an interpretation model based on a lithology triangle of Light tuffite-Heavy tuffite-quartz. The model assumed that the cementation factor (m) increased with increasing tuffite content, and that the porosities of clean tuffites could be calculated from the sonic log response, independent of tuffite content. The log responses reported by Khatchikian and Lesta (1973) can be summarized as follows.

1) Since the connate waters were generally of very low salinity, small salinity changes caused wide variations in water resistivity.

2) At low salinities, effects of clay on resistivity are more important, and a clay content evaluation becomes essential, but the natural radioactivity of some tuffites, and the occurrence of sand-streaming potential make it difficult to use the gamma-ray and SP clay indicators.

3) On the Density-Sonic cross plot, light and heavy tuffites plot above and below the sandstone line, respectively.

4) On the M-N* plot two types of tuffites were also recognized.

   a) Light tuffites which lie above the silica point (average values are: M = 0.95, and N = 0.64).

   b) Heavy tuffites which lie near the dolomite point (average values are: M = 0.78 and N = 0.55).

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*NOTE: For a brief description of M and N, see Appendix A.

The model was based on field data from Southern Argentina and gave good results for such fields, however, the assumptions made may not be valid for other formations of similar lithology.

A study carried out by Campbell (1968), on the log interpretation problems in Alaska had reported values of M and N for volcanic ash similar to the ones presented for light tuffites by Khatchikian and others (1973). Sacco (1978) utilized carbon-oxygen and spectral gamma-ray logs in formation evaluation of the tuffite-bearing oil reservoirs in Southern Argentina. A new crossplot approach involving these two logs was successfully used for lithology determination.

In 1974, Keller and others reported results of log analysis from a 1 257-m (4 123-ft) research well beneath the summit of Kilauea Volcano on the island of Hawaii. The highest recorded temperature was about 133°C (271°F). A wide variety of logs were run including temperature, gamma-gamma backscattering, neutron, induction, self-potential, natural gamma-ray, acoustic velocity, and magnetic permeability and vertical field intensity. All the penetrated formations were basalt, with generally high porosities, ranging from a few percent to nearly fifty percent. Grain densities of the encountered rocks were about 3.02 g/cm^3. The acoustic log indicated wave speeds for rocks with no porosity of approximately 5 730 m/s. Young's modulus, as determined from a full-waveform acoustic log and a gamma-gamma density log, is generally in the range from 2 to 6 x 10^{14} Pa. While the neutron-density crossplot was linear, the neutron-sonic crossplot was not, indicating perhaps that the time-average formula for sonic log response was not accurate for this lithology. Based on measurements on 400 core plugs of the basalt from the well, the following empirical relation was obtained.

$$F = 18\emptyset^{-1.05}$$

where F is the formation resistivity factor and $\emptyset$ the porosity.

West and others (1975) reported qualitative analysis of a large suite of well logs run in the geothermal Test Hole No. 2 in the Fenton Hill area of New Mexico drilled by LASL as part of their Hot Dry Rock project. The lithologies encountered were volcanics, Permian red beds, shales, and limestones before reaching the target zone of crystalline rocks including granites, granodiorites, monzonites, biotite schist, and amphibolite. Equilibrium bottomhole temperature was extrapolated to 197°C (386°F). The various electrical logs (SP, 16-in. normal, 64-in. normal, lateral, micro-devices, induction and diplog) were useful in identifying permeable zones. Except for a few zones of mafic-type rocks, which presumably have higher electron densities than does the medium generally used to calibrate the tool, the density log correlates reasonably well with the core densities. The complex lithology and the lack of data on matrix properties limited the quantitative interpretation of the density and neutron logs. Spectral gamma-ray log was very useful in distinguishing some lithologies. Full-waveform sonic log was very useful for locating fractures. Borehole seisviewer log was quite effective in delineating fractures. West and Laughlin (1976) discussed the utility of spectral gamma-ray logging in the first two wells of the LASL Hot Dry Rock project. These authors reported that spectral gamma-ray logging was useful for determining rock types, detecting fracture zones, and examining mobility of the elements U, Th, and K.

Ritch (1975) presented a fairly detailed study of a well in North Central Texas, where four separate and distinct metamorphic lithologies were penetrated over some 15 750 ft.

1) Quartzite - metamorphosed sandstone
2) Phyllite - metamorphosed derivative of fine-grained sediment

3) Calcite marble - metamorphosed limestone

4) Dolomite marble - metamorphosed dolomite

Metamorphic rocks encountered had fracture permeability and very low porosity which in some instances was recorded as negative porosity. The formation contained some highly conductive minerals, making the resistivity data less reliable. The bulk densities and the interval transit times measured were higher than the grain densities and interval transit times, respectively, usually assigned to their sedimentary rock counterparts. It is believed that such high values were caused by the presence of heavier minerals such as biotite, chlorite, and muscovite. It was also found that the SP, gamma-ray and resistivity responses could be used for distinguishing phyllite from quartzite. The M - N plot for these four lithologies resulted in a plot where these four lithologies occupied the same relative positions as would be expected for their sedimentary counterparts.

Nelson and Glenn (1975) reported a study of the influence of structural (bound) water present in the rock on the neutron log. In mineralized igneous rocks, such water can be present in the form of alteration minerals. They provide examples from two lithologies: a diabase, and an andenite-latite. Both examples are from low-porosity rocks where the bound water was found to dominate the neutron log response. They concluded that the neutron response equation must be modified to account for this effect and proposed modified crossplot relationships. For neutron-density and neutron-sonic crossplots, the bound water term was incorporated in newly defined expressions for an apparent transit time and an apparent grain density.

Hobson and others (1966) described the logging program carried out in a slim hole (2-3/4 inch) drilled in an igneous rock sequence in Canada. Their qualitative correlations indicated that the most useful log in this sequence was the neutron log. Such features as pyroxenite-dunite contacts and changes in the degree of serpentinization in dunite were clearly indicated on the log.

Keys (1976) summarized the logging problems and progress in geothermal environments. He pointed out the usefulness of in-hole gamma spectrometry, and the potential of acoustic televiewer for locating and evaluating fractures with examples from Long Valley (California) and Fenton Hill (New Mexico) geothermal areas. He presented a neutron-density crossplot from Raft River (Idaho) geothermal field.

The first published paper on the interpretation of well logs from The Geysers steam field was presented by Ehring and others (1978). The lithology in this well was meta-graywacke, greenstone, and argillite. The logging suite was gamma ray, compensated density and neutron-neutron together with temperature log. These authors reported a new log interpretation program for steam wells that calculates lithology, porosity, steam entry zones, and steam quality. These authors pointed out that more research and field experience will be necessary before their work is completed.

Besides above published case histories, several workers have made oral presentations of geothermal log interpretation results in technical meetings. Some unpublished reports on this subject exist in the files of resource companies.

Laboratory Investigations:

In the past few years, increasing numbers of petroleum-bearing formations where pyrite is present have been reported. Pyritization is also seen in geothermal fields. It has been found that the effect of disseminated pyrite disturbs well log responses in an unpredictable manner. In an essentially experimental investigation, Clavier and others (1976) made laboratory measurements on field cores, sand packs, and chunks of pyrite.

The effect of pyrite on the porosity logs was reported to be small for Sonic and Neutron logs, but large for the Density log. The Density log was thought to be more useful in some cases for determining pyrite content than porosity. The electrical properties of pyritic rocks, for the range of frequencies used in resistivity logging, were found to be strongly dependent on the distribution of pyrite and the frequency of the measuring current. In the usual case where the concentration of pyrite was too low to provide metallic electrical continuity through the pyrite, the low-frequency resistivity measurement remained essentially undisturbed. Increasing the frequency appeared to lower the measured value of resistivity in a manner which had been related to the frequency, pyrite content, and water resistivity. The frequency effect was essentially independent of temperature and water saturation and might be corrected using an appropriate chart. When electrical continuity existed through the pyrite phase, the measured resistivity decreased dramatically at any frequency and could not be used for saturation computation. Recommendations concerning the logging program were given.

As part of a continuing laboratory study, Keller (1977) reported that the formation resistivity factor of volcanic rocks were consistently higher than would be indicated by Archie's formula for the same porosity. They experimented with core samples of volcanic rocks from the Snake River Plain (Idaho), Modoc Plateau (Oregon), Cascade Range (Oregon), Central Nevada, and Columbia Plateau (Washington). This author also reported that the compressional as well as shear wave velocities appeared to be independent of porosity.

Hence it was concluded that the acoustic velocity measurements could not be used as a guide to porosity in volcanic rocks.

Trice and Warren (1977) reported a laboratory experiment on two granodiorite samples from Fenton Hill (New Mexico) for correlation of acoustic velocity and permeability. For pressures below about one kilobar, the permeability data agreed well with a function involving the cubic power of the compressional velocity modulus. This relation was suggested from a comparison of the Kozeny relation for permeability to the form of the functional dependence of elastic moduli on porosity and pore strains. The correlation suggested that in such rocks, crack strains were essentially linear with pressure and that the same network of cracks controlled both permeability and elastic properties.

Simmons and Nur (1968) observed that the velocity of compressional waves and electrical resistivity in granite in situ measured in two 3-kilometer boreholes exhibited very little variation with depth, in contrast to the variation predicted from laboratory measurements on dry samples. These authors indicated that these observations can be explained either by the absence of small open cracks in the rocks in situ or by the effects of complete saturation with water. Roegiers and Thill (1976) performed rock characterization tests both in the field and laboratory in connection with the LASL Hot Dry Rock project. They found that the density, sonic velocity, and elastic properties determined from log interpretation showed reasonably good agreement with the ones obtained under similar laboratory conditions. The minor discrepancies could be explained, according to these authors, as proposed by Simmons and Nur (1968). Significant discrepancies were encountered by Roegiers and Thill in determining porosity in the laboratory and from logs. They concluded that estimation of porosity from either sonic or neutron log is impractical in such basement rocks.

In the logging and petroleum engineering literature, many authors have reported both reversible and irreversible effects of temperature on rock properties. For example, refer to Weinbrandt (1972) and Aruna (1976) for permeability, Somerton (1973) for thermal properties of rocks, Sanyal and others (1972) for electrical resistivity, Timur (1976) for sonic wave velocities, and Sanyal and others (1974) for a review of temperature effects on all important petrophysical properties.

Somerton and others (1974) measured sonic velocities, bulk and matrix compressibilities and thermal conductivities on a group of outcrop sandstones and a group of siltstone cores from the Imperial Valley geothermal area in California. The measurements were carried out at temperatures as high as 200°C and pressures to 16 000 psi. They found a decrease in sonic velocities with increase in temperature as also observed by Timur (1976). Somerton and others (1974) also found an increase in sonic velocities with increase in pressure and with liquid saturation. If this effect of temperature on sonic velocities is ignored, overestimation of porosity from sonic logs could result.

THE STATUS OF GEOTHERMAL LOG INTERPRETATION

From the foregoing discussion it is apparent that while there are many problems still plaguing geothermal logging, some log interpretation has been possible in many cases. As logging instrumentation improves, interpretation techniques should also improve. Based on the experimental results it is apparent that the interpretation techniques for the geothermal well logs must take into account the effect of temperature on rock properties and the difference between the petrophysical properties of geothermal reservoir rocks and the sedimentary rocks that comprise petroleum reservoirs.

The state of the art of at least qualitative interpretation of geothermal well logs can be summarized from Table 1.1 (Sanyal and Meidav, 1977). Table 1.1 summarizes the utility of the commonly available well logs for geothermal reservoirs of the nonsedimentary lithology. For sedimentary lithology, utility of these logs will be similar to their utility in the petroleum industry. Table 1.1 does not include the use of multilog analysis and various computer techniques, which can have significant synergistic effect on geothermal formation evaluation. The only published paper on synergistic, computer interpretation of a suite of geothermal well logs from a dry steam field is that by Ehring and others (1978). The program has apparently been successful. However, longer field experience will be necessary before it can become standardized and widely used. For sedimentary geothermal systems such as the Imperial Valley of California and the Mexicali Valley of Mexico, a modified version of Schlumberger's SARABAND sand-shale analysis program has been successful. Schlumberger's complex lithology computer model (CORIBAND) has been applied with some success to the Raft River geothermal field in Idaho. Members of this project team have performed computer interpretation of geothermal well logs both for private clients and as a part of this project. Two examples of such interpretations are given in this report under Task 4.

Any quantitative interpretation of well logs needs two basic inputs: a pore model and the data on the log response of the matrix forming the rock. The state of the art of geothermal well logging indicates that these two aspects need improvement, which is one of the aims of this project. Tasks 5 and 6 in this report include details of these aspects. Detection (and delineation) of natural or induced fractures is a prime aim of most geothermal logging. The state of the art and efforts under this project in the area of fracture detection and delineation are discussed under Tasks 5 and 6 in this report.

The interpretation of temperature logs and estimation of the equilibrium (or static) temperature profile in a well bore are important aspects of geothermal well log analysis. An account of the state of the art and the proposed effort under this project in this area is presented under Tasks 5 and 6 in this report.

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TABLE 1.1

UTILITY OF VARIOUS WELL LOGS IN NON-SEDIMENTARY LITHOLOGY

(From Sanyal and Meidav, 1977)

LOG TYPE	COMMENTS
1. Self Potential	Often poorly developed; Unreliable in massive igneous or metamorphic sections; Works in some fractured igneous and metamorphic sections; Usually not useful for correlation.
2. Electrical Resistivity	Mostly off scale in massive igneous and metamorphic sections; Can be helpful in locating fractures; Short spacing resistivity may be affected by the short-circuiting effect of borehole fluid; Focussed devices may be helpful for very resistive formations.
3. Acoustic Devices	BHC sonic log works well unless there is significant hole enlargement; May be useful for correlation; Matrix velocity values may not be known; Useful for overlay and crossplot techniques; Full-wave sonic log valuable in locating fractures; Borehole televiewer valuable for locating fractures and delineating its orientation; Frac finder log may be useful.
4. Neutron Devices	Responses from unfamiliar lithology may be difficult to assess; May be useful for correlation.
5. Density	Useful in estimating porosity and lithology; Caving may be a problem; Log response from unfamiliar lithology difficult to assess; Useful for correlation.
6. Gamma Ray	Useful for correlation; Spectral gamma ray useful for lithology identification.
7. Drilling Log	Drilling rate log useful for locating fracture zones and changes in lithology; Drill cuttings log useful for lithology identification; Useful for correlation.
8. Caliper	Useful in resolving many log quality problems; 6-arm caliper can be used in determining dip of fracture-zone washout; Use in judging hole condition.
9. Dip Meter	Not always useful because of lack of laminated structure; Dip of fractures may be unreliable.
10. Temperature	Useful for assessing temperature gradient, and other standard uses of temperature log.

NOTES

TASK-2: CLASSIFICATION OF GEOTHERMAL RESERVOIR TYPES

Introduction and Rationale

This task calls for definition of geothermal reservoir types relevant to well log analysis. In other words, out of this task should emerge one or more classification schemes for geothermal reservoirs from the viewpoint of well log analysis; the hope being that the vast number of known geothermal reservoirs can be grouped into a small number of reservoir classes each with its distinct set of log responses and typical log analysis problems. The first step in developing such classification schemes is to examine the important reservoir characteristics having bearing on log response.

The following reservoir and fluid properties usually determine the log response of a reservoir.

1. Lithology
2. Fluid Phase
3. Fluid Chemistry
4. Reservoir Temperature
5. Pore Geometry
6. Certain Overall Geological Factors

Lithology is perhaps the most important reservoir property so far as log response is considered, for rock matrix occupies the major fraction of the bulk volume of a reservoir. Fluid phase is important because water and steam have different log responses as do oil and gas in petroleum reservoirs. Moreover, as will be pointed out in the next section, there are certain special problems in logging of dry steam reservoirs as compared to hot water reservoirs.

Except for hot, dry rock systems, geothermal reservoirs are entirely saturated with water (in liquid or vapor phase). However, the chemistry of geothermal waters varies extensively depending on the nature and quantity of dissolved solids and gases, far more so than for oilfield waters. The amount of total dissolved solids (TDS), or its "equivalent sodium chloride concentration" is usually an adequate description of the chemical nature of oilfield waters. In geothermal systems, TDS alone is insufficient to describe fluid chemistry because sodium chloride is not necessarily the predominant constituent.

Reservoir temperature affects geothermal well logging in two respects: geothermal well temperature often exceeds the tolerance of many of the standard logging tools, and temperature affects most rock and fluid properties. The nature and geometry of the pore spaces have a strong influence on the sonic and resistivity log responses from a formation, for the pore spaces control the path of the sonic waves and electric current through the formation. Detection of fractures in an otherwise massive lithologic section is often the main purpose of well logging in the geothermal industry. Pore geometry is thus an important property.

Besides the rock and fluid properties mentioned above, there are certain overall geological factors that affect log response. Each geological province has an assemblage of rock and fluid properties that gives rise to a set of log responses characteristic of that province. In the petroleum industry, for example, one speaks of the Gulf Coast, the Rocky Mountain area, California, the North Sea, etc., as regards typical log analysis problems. Similarly in the geothermal industry, regional (in the geological context) differences in log analysis approaches are likely to emerge in the future.

SCHEMES FOR CLASSIFICATION OF GEOTHERMAL RESERVOIRS

From above discussions, it is apparent that as regards well log analysis, one can classify geothermal reservoirs according to any of the reservoir and fluid properties listed in the previous section. In this section, these various classification schemes will be examined in detail. Table 2.1 is a list of such classification schemes and reservoir types under each scheme.

I. CLASSIFICATION ACCORDING TO FLUID TYPE AND TEMPERATURE

A geothermal reservoir may be saturated with water or steam. In some cases, a primary steam cap may exist above a hot water zone. Development of a secondary steam cap or steam saturation around well bores in a hot water reservoir is possible, if during reservoir depletion the fluid pressure falls below the vapor pressure of water at the prevailing reservoir temperature. Development of steam saturation has been observed in the Wairakei hot water reservoir in New Zealand. In the geothermal industry, the commodity sought after is "heat"; as such a geothermal "reservoir" need not contain any fluid so long as it contains sufficient heat and has an acceptable temperature level. One such "hot dry rock" system in the Jemez Mountains of New Mexico is being developed as a prototype by the Los Alamos Scientific Laboratory.

The temperature in a hot water reservoir may range anywhere from ambient to near the critical temperature of water, 360°C (680°F). The Niland (or Salton Sea) geothermal reservoir in Imperial County, California, has a reservoir temperature near the critical temperature of water. Geothermal reservoirs under development in the United States for electric power production are all at temperatures above

TABLE 2.1
GEOTHERMAL RESERVOIR CLASSIFICATION SCHEMES

I. According to Fluid Phase & Temperature:
   A. Steam
   B. High-Temperature Water: >204°C (400°F)
   C. Moderate-Temperature Water: 149-204°C (300-400°F)
   D. Low-Temperature Water: <149°C (300°F)
   E. Dry

II. According to Lithologic Type:
   A. Sedimentary
   B. Metamorphic
   C. Igneous (crystalline & glassy)
   D. Volcanic Ash and associated sediments, tuff
   E. Breccia
   F. Hydrothermally Altered

III. According to the Geologic Province:
   A. Basin & Range
      a. Wasatch Front
      b. Central
      c. Western Margin
   B. Northwest Volcanic
      a. Snake River
      b. Cascade Range
      c. Other
   C. Salton Trough
   D. Northern California Coast Range
   E. Rio Grande Rift & Colorado Plateau Borderland
   F. Hawaii
   G. Alaska

IV. According to Pore Geometry:
   A. Sedimentary Intergranular Porosity
   B. Fracture
   C. Vesicular or vuggy porosity

V. According to Salinity and Fluid Chemistry:
   A. Low salinity: <5 000 ppm
   B. Moderate salinity: 5 000 - 35 000 ppm
   C. High salinity: 35 000 - 100 000 ppm
   D. Hyper saline: > 100 000 ppm
   E. Dry

149°C (300°F), which is considered the lowest economic temperature limit for commercial geothermal power generation under current technology. However, reservoirs with water temperatures well below 93°C (200°F) are being considered for development for nonelectrical uses. The higher the temperature of a geothermal water, the higher is the thermodynamic efficiency of energy conversion and the better is the associated economics. Thus it is logical to classify geothermal reservoirs not only according to the fluid type (steam, water, dry) but also according to the fluid temperature.

For the purpose of this study, hot water geothermal reservoirs have been tentatively classified as being of a high: greater than 204°C (400°F), intermediate: between 149°C (300°F) to 204°C (400°F), or low: less than 149°C (300°F) temperature class.

Figure 2.1 presents the temperature distribution of the known hot water reservoirs in the U.S., derived from the data reported in the Circular 726 of the U.S. Geological Survey (1975). Figure 2.1.a shows the number of known "hydrothermal convection systems" in each of a number of temperature classes starting from 93°C (200°F). It is obvious from the figure that higher temperature reservoirs are less frequent. Of the 297 hot water reservoirs listed in the Circular 726 of the U.S.G.S., 188 belong to low-temperature class, 92 to intermediate, and 17 to high. Figure 2.1.b shows the estimated total heat contained in the known hot water reservoirs under various temperature classes. It appears that both the low-and high-temperature classes have much more heat content than the intermediate class. However, the low-temperature class being unsuitable for electrical power production is economically less attractive. The high-temperature class is the most profitable of the three, but also is less frequent in occurrence.

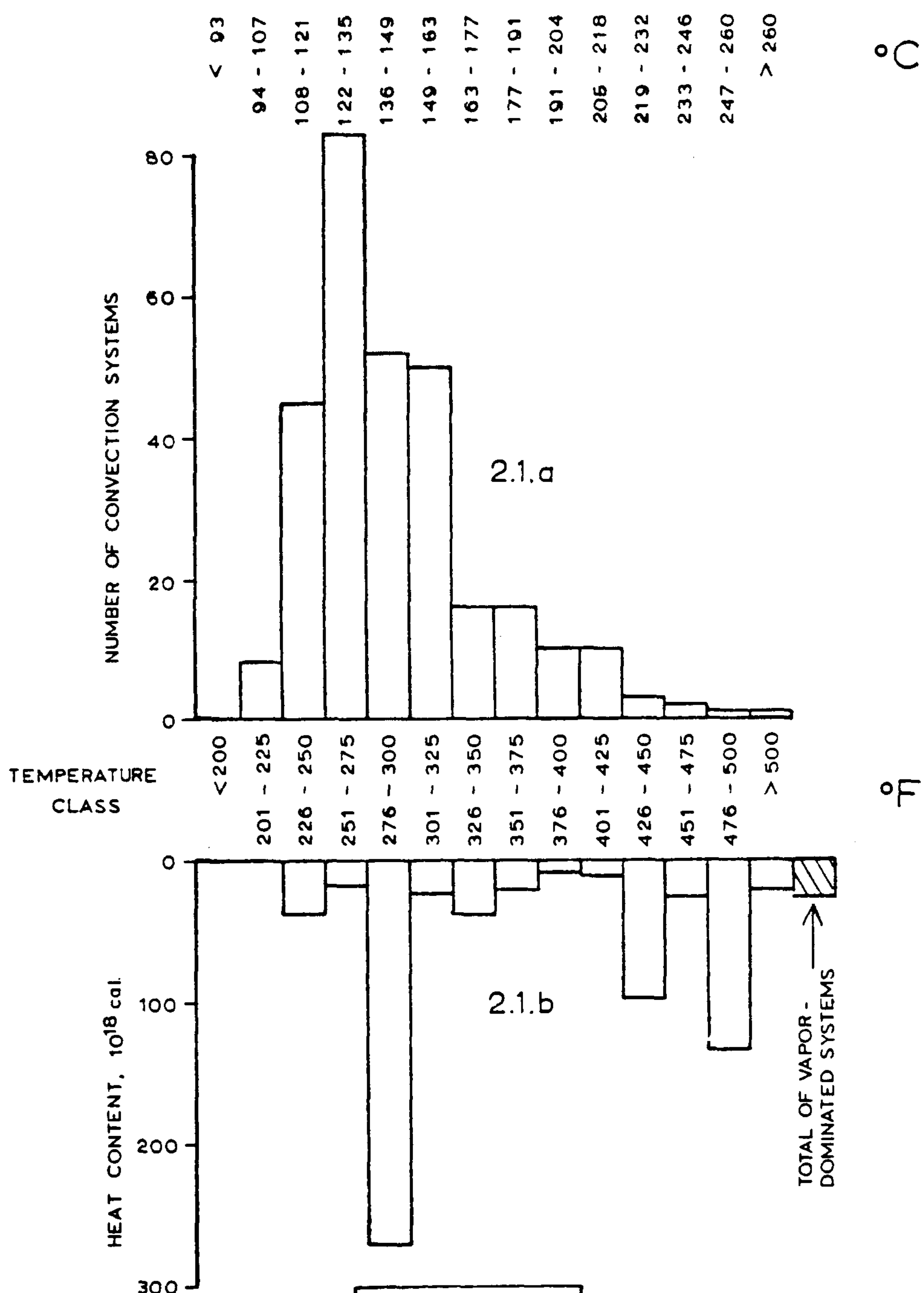

FIGURE - 2.1

TEMPERATURE DISTRIBUTION OF KNOWN HOT WATER RESERVOIRS IN THE U.S.

Dry steam reservoirs are rare, there being only five proven dry steam reservoirs in the world: The Geysers in California, Lardarello and Monte Amiata in Italy, and Matsukawa and Onikobe in Japan. All of these are under production. As of 1976, these five reservoirs were responsible for 965 MW out of a total worldwide geothermal power production of 1 500 MW -- a share of 65 percent. While rare in occurrence, the dry steam reservoirs are prolific sources of power. Only two other possible such fields have been identified in the U.S. so far: one in the Mt. Lassen National Park, California and the other in the Yellowstone National Park, Wyoming. All the known dry steam reservoirs exhibit almost the same steam temperature and pressure in the reservoir -- around 240°C (464°F) and 3.4 MPa (500 psi). This temperature and pressure condition corresponds to the maximum enthalpy condition for steam in contact with water. These conditions cause unusual problems in logging dry steam wells.

Out of over a hundred steam wells drilled in The Geysers, only a few have been logged because most attempts to log such wells have encountered serious problems of tool and cable malfunction due to high temperature. In The Geysers, production takes place between the depths of 180 and 2 740 meters (600 to 9 000 feet). Below about 300 meters (1 000 feet), the hydrostatic pressure in the wellbore exceeds the reservoir pressure. At the maximum production depth, the hydrostatic pressure reaches 26.5 MPa (3 800 psi), which is an order of magnitude higher than the reservoir pressure of 3.4 MPa (500 psi). Thus the steam reservoirs are underpressured, creating uncontrollable lost circulation problems if drilled with mud. The current practice at The Geysers is to drill with water or mud to the bottom of the water-bearing strata, case the well and continue drilling with air down to the steam reservoir. Sonic, dc resistivity and self-potential logs are not run in steam wells because the well is filled with air or dry steam instead of a liquid.

Besides, the resistivity of the steam-saturated formation is too high to allow any meaningful interpretation of an electrical resistivity log. The current practice for very hot water wells is to cool the hole by circulation of a cold fluid for a period of time before logging. This is not possible for the steam wells at The Geysers because of the abnormally low reservoir pressure. Natural gamma, neutron, and density logs have been run successfully in some steam wells.

To date, no written regulations exist for radioactive source abandonment for geothermal wells in the State of California. The use of radioactive materials in California (except for uranium and plutonium) is governed by the State Department of Health, Division of Industrial Safety, Radiological Health Section. This undoubtedly is a deterrent to running complete suites of well logs.

The whole gamut of standard well logs can be run in a hot water well of the low-temperature class. Such logs can be run in hot water wells of the intermediate-temperature class if the well can be cooled down by circulation to below 177°C (370°F), which is the current practical limit of effective operation for most logging devices. It may be impractical to cool down many of the high-temperature class wells sufficiently for logging with the standard tools. Sandia Laboratories, as well as some logging service companies, have developed high-temperature logging tools and cables which can withstand temperatures of up to 260°C (500°F). Such devices are being tested and refined. Even when these devices become commonplace, some of the hazards of logging a hot well may still persist.

Suites of temperature, dual induction with a shallow focussed device (or less commonly, induction log alone), neutron and density with associated S.P., gamma-ray and caliper logs have been run in many hot water wells. Dip meter, acoustic and production logs have been run in some of the cooler wells.

Hot dry rock systems do not have any significant porosity and permeability before being fractured artificially. Hence, electrical logs have limited utility for quantitative analysis before fracturing. However, these logs, including single-point resistivity surveys, when run before and after artificial fracturing may delineate the intervals of successful stimulation. Other logs such as gamma-ray, spectral gamma ray, neutron, density and acoustic logs can be used to identify lithology and estimate mechanical properties of the formation, such as fracture pressure gradient. After artificial fracturing, several logs can be used to detect and evaluate the fractures. Full wave train sonic log, borehole televiewer, and possibly SP (may indicate streaming potential in fracture zones) and resistivity (lower resistivity in fracture zones) logs may be useful for this purpose.

Another motivation for classifying reservoirs according to temperature is that temperature level can have a significant effect on many petrophysical properties of reservoir rocks [Sanyal and others (1974)]. For example, it is well known that permeability declines with temperature [Weinbrandt (1972), Casse (1974), Aruna (1976), etc.] For this reason, the practice of normalizing of geothermal well logs by use of core data taken at ambient conditions is questionable. Unfortunately, the present state of knowledge of the effects of high temperature and pressure on reservoir rocks is primitive. It can be said, however, that the higher the temperature level, the greater are such effects.

II. CLASSIFICATION ACCORDING TO LITHOLOGIC TYPES

From the point of view of lithology, petroleum reservoirs are usually classified into two broad classes; sand-shale lithology and carbonate lithology (with or without associated sand, shale, sulfates, etc.). Only rarely do petroleum reservoirs exhibit other lithological components such as pyrite, lignite or coal, tuff, etc. Conventional log analysis techniques were thus developed for sedimentary rocks, particularly for sandstone, shale, limestone, dolomite, and anhydrite lithologies. Geothermal reservoirs on the other hand, can have any lithology -- sedimentary, igneous or metamorphic. In such reservoirs, one often encounters "unfamiliar" lithologies such as crystalline igneous and metamorphic rocks, vesicular volcanic rocks, glassy or crystalline volcanic rocks, volcanic ashes, welded volcanic rock fragments, hydrothermal deposits and alteration products. Even sedimentary geothermal reservoirs often exhibit profuse igneous intrusion, contact metamorphism, and hydrothermal alteration. Unlike sedimentary basins, igneous and metamorphic provinces, particularly those which have undergone hydrothermal alteration, often display a high degree of heterogeneity. Hence, in the same geothermal reservoir (igneous or metamorphic type), lithology may be entirely different from one horizon to another or from well to well.

An unfamiliar lithology poses several problems in logging. Standard calibration of most well logs is inadequate for such lithologies. Well logs are calibrated and tested against known lithologies common in the petroleum reservoirs. When an "unusual" rock type is encountered, the log response may appear strange. Some correction may be necessary to such a log response. For most unfamiliar lithologies, such corrections cannot be estimated. For example, in the Hot Dry Rock Project of LASL, the well GT-2 shows some zones where an increase in bulk density of the massive formation is not accompanied by a corresponding decrease in sonic travel time. (West and others, 1975). One possible explanation of this phenomenon is that the mafic rocks encountered in these zones may have higher electron densities than does the medium used to calibrate the density logging tool. In the same well a zone shows a decrease in sonic travel time corresponding to an increase in bulk density, but the apparent neutron log porosity increases (West and others, 1975). This has been explained as being due to the presence of a material with a high neutron capture cross section, possibly a mafic type of intrusion. Calibration data are not available to resolve this type of problem. In the same well, a zone shows an increase in bulk density and an apparent increase in neutron porosity, which has been considered to probably indicate a material with a high capture cross section to neutrons and high electron density. Standard log interpretation techniques and charts are often inadequate in dealing with unfamiliar lithologies. For example, in crossplotting multiple porosity log data, points for some geothermal zones fall outside the range of the standard crossplot charts. In some wells in the Raft River geothermal field in Idaho, bulk densities often exceed 3.0 g/cm^3 which is the maximum limit of density values presented in all standard charts. During logging in an unfamiliar lithology and subsequent analysis of logs, some log quality problems may remain undetected. Matrix properties (such as bulk density, sonic travel time, matrix neutron porosity, neutron capture cross section) of igneous and metamorphic rocks are unavailable in the logging literature. Matrix properties are available for only a few of the minerals that form igneous and metamorphic rocks.

The tentative classification of geothermal reservoirs based on lithology is shown as Scheme II in Table 2.1. The logging response and associated log analysis problems of sedimentary geothermal reservoirs are similar to those for petroleum reservoirs. Sedimentary geothermal reservoirs may be of the sand-shale sequence type (such as Heber, East Mesa and Brawley fields in Imperial Valley, California), sand-shale sequence with igneous, intrusives or hydrothermal alteration (for example, Salton Sea field, Imperial Valley, California) and sand-silt-shale sequence interlayered with volcanic ash, tuff, and volcanic flow (for example, Raft River, Idaho). No major geothermal reservoir has been discovered in carbonate rocks as yet. It is anticipated that the state of the art of well log analysis will be adequate in dealing with sedimentary geothermal lithology. However, some modifications in analysis may be required to take into account contact metamorphism, hydrothermal alteration, etc., when encountered. Computer-processed sand-shale analysis logs have been successfully run in the Imperial Valley reservoirs. In Raft River, Idaho, computer-processed complex lithology logs have been obtained.

For the other lithologic types, the state of the art of well log analysis is inadequate. It is hoped that as a result of this study, systematic log analysis techniques will evolve for these lithologic types. The conventional complex lithology analysis aided by cross plots, histograms and computer processing can be applied to igneous and metamorphic-type lithologies, but matrix responses of the mineral constituents are often unknown and mineral composition may vary drastically from zone to zone. Incorporation of the spectral gamma ray log with these techniques can be useful in identifying some lithologies. (West and others, 1975).

III. CLASSIFICATION ACCORDING TO THE GEOLOGIC PROVINCE

Each geological province displays its own characteristic assemblage of petrophysical properties. For this reason, generally accepted log analysis techniques have evolved for each major petroleum province such as the Gulf Coast, the North Sea, etc. Such tradition is already evolving in the geothermal industry. For example, the log analysis techniques and procedures for the Imperial Valley, California geological province are standardized for all practical purposes -- sand-shale analysis techniques based on induction (or dual induction -- shallow focussed device combination) and the three porosity log suite. Log analysis procedures for other geothermal provinces are still in the experimental stage. Hence, it is important to try to classify all known geothermal areas of the United States into a limited number of geological provinces, to define the characteristic logging responses from each province, and to suggest optimum log analysis procedure for each province.

Almost all commercially significant geothermal reservoirs in the United States occur west of the Rocky Mountains in areas of geologically young (Late Cenozoic) or present day tectonism or volcanism or both. Such areas are characterized by recent silicic volcanism, high heat flow, profuse faulting and strong seismicity. The vast majority of the known geothermal reservoirs lie in the seven geological provinces listed under the classification Scheme III in Table 2.1. However, as shown in Table 2.1, these provinces can be divided into distinct subprovinces. Figure 2.2 is a map showing the location of the geological provinces mentioned above. Due to the established interpretation techniques of the petroleum industry, the "geopressured" geothermal reservoirs of the northern Gulf of Mexico Basin have been excluded from this classification.

<u>Basin and Range Province</u>: This geological province covers the entire state of Nevada, as well as parts of Utah, Oregon, California, Idaho, and Arizona. Two major belts of geothermal resource sites stretch along the eastern and western margins of the Basin and Range province. The eastern belt

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FIGURE 2.2 GEOTHERMAL EXPLORATION AND DEVELOPMENT IN THE WESTERN UNITED STATES 1968-1975, covers the Wasatch Front and the area just east of it and covers parts of Idaho and Utah. The western belt passes through Oregon, California, and Nevada. The central region covers Nevada and Arizona. Young silicic and basaltic volcanism and faulting are concentrated along the eastern and western belts.

The eastern belt lies just west of the Wasatch Front, which is the faulted boundary between the Basin and Range province and the Colorado Plateau-Rocky Mountains. This belt extends north-south across the entire state of Utah and into Southern Idaho, for a distance of some 560 kilometers; its width is about 100 kilometers. Geologically, the belt is similar to the western one described above; however, some geothermal reservoirs (such as Roosevelt Hot Springs) here have higher temperature. Exploratory drilling at Roosevelt Hot Springs indicates a high-temperature hot-water reservoir that is of commercial quality and quantity sufficient for electric power generation (C. W. Berge, 1978, personal communication).

An important geothermal area in the center of the Basin and Range province is Beowawe, Nevada, where hot water at over 200°C (392°F) has been encountered in drill holes. Other prospects have been drilled in Nevada, Oregon, and Arizona, and still others in these states and New Mexico are being explored.

The western belt extends from Lakeview, Oregon through Surprise Valley and Long Valley, to Coso, California for a distance of some 560 kilometers; it has a maximum width of 130 kilometers in the vicinity of Reno, Nevada, where it extends eastward across the Carson Desert. Geothermal reservoirs here appear to be entirely of the hot water type.

Information available on the log response and log analysis problems in this province is limited. However, it appears that the main log analysis problems in this geological province are coping with unfamiliar lithologies (intrusive and extrusive volcanics) and detection of fracture zones.

<u>Northwest Province</u>: This province covers major portions of the states of Washington, Oregon, and Idaho as well as parts of California, Nevada, Wyoming, and Montana. The Snake River Plain and the High Cascade Mountains form two distinct subprovinces.

The Snake River Plain extends over Idaho and Oregon and is covered by vast thicknesses of young basaltic lava flows. Exploration to date indicates that the reservoirs in this region are relatively large in volume but have low temperature. Most of the reservoirs in the Snake River Plain are of the low-temperature class according to our classification Scheme I. For example, Raft River, Mountain Home, and Bruneau-Grandview reservoirs of Idaho.

The High Cascades subprovince extends from British Columbia through Washington and Oregon to Mount Lassen in California. The main characteristics of this region are copious outpourings of basaltic and andesitic lavas from 2 to 10 million years old, and many recently active volcanoes, such as Hood, Shasta, Lassen, Baker, Three Sisters, and St. Helena. Occasional fumaroles are present, such as in the Lassen National Park. At Klamath Falls, Oregon, a low-temperature geothermal reservoir has been used for space heating for several decades. Considerable exploration is taking place in this region and high enthalpy commercial geothermal reservoirs may be discovered in the future.

In the rest of the Northwest volcanic province, only low-temperature geothermal reservoirs have been discovered, such as at La Grande, Oregon.

Although the log responses and log analysis problems may differ between the three subprovinces, the Northwest Volcanic province is characterized by basaltic, rhyolitic and andesitic lava flows, volcanic ash, and interlayered beds of sediments. Complex lithology analysis techniques have been used with some success in Raft River, Idaho. However, responses of the volcanic flows and ashes, particularly after hydrothermal alteration, are often unpredictable. Vesicles and fractures provide the main storage and flow capacity in most of these reservoirs. As such, fracture detection from well logs is a necessity in the area.

Salton Trough: A most important and well-known geothermal area in the United States, as far as commercial potential is concerned is the Salton Trough, which covers the Mexicali Valley of Mexico and the Imperial and Coachella Valleys of California. This area lies at the northern end of the major rift zone extending the entire length of the Gulf of California. This area is characterized by high heat flow, steep geothermal gradient, faulting, fracturing, and occasional silicic volcanism. The trough contains up to 7 000 meters of Tertiary and Quaternary continental sediments.

There are at least five major geothermal reservoirs in this province. At Cerro Prieto, Mexico, a 75-megawatt geothermal power plant has been in operation since 1973 and a second 75-megawatt plant is under construction. This is a high-temperature and moderate salinity (according to our classification) reservoir. At Niland (Salton Sea), a high-temperature and hypersaline reservoir has been identified since the early 1960's. Extensive testing of this reservoir is in progress, but its hypersaline brine and the consequent corrosion and scaling problems have prevented commercial exploitation so far. Three other reservoirs of moderate temperature and moderate to high salinity occur in the Salton Trough; these are East Mesa, Heber and Brawley.

The main lithology in this province is deltaic sand-shale sequence. Hence, standard sand-shale log analysis techniques have proven useful in this area. The sandstones can be poorly consolidated to highly cemented (or metamorphosed) and fractured. Occasionally igneous intrusives may be present, such as at Salton Sea. Hydrothermal alteration is seen in places. Determination of approximate salinity of the water from well logs is a useful exercise in this area because of the complex distribution of saline and fresh water aquifers. The area is a prime agricultural province and yet, is a semidesert relying solely on irrigation by Colorado River water brought through canals. Hence, from the environmental as well as from a water management point of view, a knowledge of the salinity profiles in the wells is important. Well logs can be used to derive salinity profiles.

Northern California Coast Range: This province is relatively small in size, however, it contains the most prolific geothermal field in the world: The Geysers. This geothermal field lies in the immediate vicinity of the Clear Lake and Sonoma Volcanic fields, which are geologically young and silicic in nature. The reservoirs are formed by intensely faulted and fractured graywacke. This is a subhydrostatic, dry-steam field. Low-temperature hot water reservoirs have been utilized in several locations in this province.

The logging problems of dry-steam reservoirs have been discussed before. Because of the limited logging suites available and the complex lithology, log analysis is difficult for The Geysers field.

Rio Grande Rift and Colorado Plateau Borderland: The Rio Grande Rift is up to 160 km wide, and extends from the vicinity of El Paso, Texas to central Colorado -- a distance of over 650 km. The characteristics of this province are tensional faulting, basin subsidence, and repeated intrusion and extrusion of young, silicic and basaltic igneous rocks.

A number of potentially valuable prospects are present in this zone. At Valles Caldera, New Mexico, a commercial high-temperature field (fractured tuff reservoir) is being developed. Close to that field, Los Alamos Scientific Laboratory is experimenting on energy extraction from hot, dry rocks. The reservoirs are usually in fractured crystalline rocks, the main logging problems being deciphering unfamiliar lithology and fracture detection.

IV. CLASSIFICATION ACCORDING TO PORE GEOMETRY

Well log analysis traditionally has emphasized the evaluation of the amount of a specific fluid in a given volume of porous rock. This can be accomplished by estimating the porosity and fluid saturations from well logs. However, these estimates are concerned mainly with the storage capacity of a reservoir. To be commercial, a reservoir must also have sufficient flow capacity, which is controlled by porosity as well as pore geometry. Two rocks of the same porosity can have quite different flow capacities if their pore geometries are different. For example, consider two porous media of the same porosity: one consisting of a single planar fracture and the other a bundle of parallel cylindrical pore channels (simulating intergranular porosity) across any unit cross-sectional area of the media. It can be shown that either 100 parallel cylindrical pore channels of 1-μm radius or a single fracture of 0.0314-μm width will give the same porosity; however, the permeability of the former will be 4.8 times the permeability of the latter. In geothermal systems, fracture permeability is the most frequent, followed by intergranular and vesicular (or vuggy) type in frequency of occurrence. The majority of the reservoirs with crystalline igneous and metamorphic igneous rocks possess fracture permeability only. The reservoirs with sedimentary lithology usually possess intergranular permeability; fracture permeability may develop if the sediments are well consolidated, hydrothermally altered or metamorphosed. Vesicular pore geometry is seen in some volcanic flows, particularly Basaltic flows. Usually vesicular pore geometry gives rise to high permeability, an extreme case being that of pumice, which is an extremely porous volcanic rock. In general, fractured rocks display poor storage capacity but very high permeability. For example, at The Geysers, the porosity is of the order of 2 to 5 percent, while the permeabilities in producing zones can be many darcies. Intergranular pore geometry is usually associated with high porosity and moderate to low permeability. In the Imperial Valley, for example, a typical reservoir has about 20 percent porosity and 200-millidarcy permeability. If the lithology is very shaly or has a high content of volcanic ash, the intergranular permeability may be very low.

The importance of classifying geothermal reservoirs according to their pore geometry lies in the fact that different pore geometries may have different log responses. For example, sonic wave propagation through rocks is generally unaffected by the presence of secondary porosity, i.e., fracture and vuggy porosity, in an intergranular-type medium. Thus, in such rocks, the porosity calculated from the sonic log is primary porosity and is lower than the porosity values obtained from density and neutron logs, which measure the total porosity. The distinction between primary and secondary porosities may be difficult for some geothermal reservoirs. For example, the vesicular pore space in a volcanic flow constitutes primary, rather than secondary, porosity. The sonic log may be affected by this type of porosity.

Electrical resistivity logs may be affected by the pore geometry. For example, isolated fluid-filled pore spaces (such as hydrothermal inclusions or some vesicles) cannot be detected from electrical logs. Also, the "cementation factors" of fractured rocks are different from that of intergranular-type rocks. Thus, the value of the cementation factor can be used as a means of detecting fractures from well logs. Another possible means of using electrical logs to detect fractures is to compare the formation resistivities derived from a deep induction tool (approximately R_t) and a shallow focussed device (approximately R_{xo}). R_{xo} is usually greater than R_t (because the mud filtrate resistivity is greater than the formation water resistivity). But in fracture zones, the apparent R_{xo} may be less than R_t, because the shallow focussed device reads vertical resistivity and consequently will be affected more by a vertical fracture than the induction log, which reads horizontal resistivity. In massive crystalline rocks, formation resistivity is usually extremely high; except for focussed devices, measured resistivity is affected by the short-circuiting effect of the mud in the borehole. The self potential log may be used in some cases for fracture detection. Usually the SP curve appears to be featureless and wandering through massive lithologies; but in fracture zones significant streaming potential and hence an SP may be generated.

Sonic amplitude logs, which measure both compressional and shear wave amplitudes, can sometimes be used to detect fracture zones. Over fracture zones, sonic wave amplitude decreases sharply, the compressional wave being more affected by vertical or high-angle fractures and the shear waves by horizontal or low-angle fractures. Full wave train sonic logs may be used for visual inspection for fractures. However, these are qualitative approaches and can give only an approximate idea of the extent of fracturing. A quantitative estimate of the fracture porosity can sometimes be obtained from the difference between the porosity from density or neutron log and that from the sonic log, as discussed earlier.

It is apparent from the above discussion that fractures can possibly be detected, at least qualitatively, by several methods. The detection of vesicular or vuggy porosity may not be easy. Although it may be possible to understand the pore geometry, and estimate the amounts of primary and secondary porosities in a geothermal reservoir, the estimation of permeability is fraught with problems. Except for very limited applications of nuclear magnetic logs in the oil industry, permeabilities have always been obtained from core data or well tests. Usually, an empirical relation between permeability and porosity is established from the core data from a well, and then permeability is estimated from log-derived porosity values by applying that relation. For consolidated, intergranular formations, this approach is reasonable and has been used in the Imperial Valley. If the formation is either poorly consolidated or fractured, core-derived permeability may be inaccurate and often misleading. When comparing core data (which is usually taken at ambient conditions) and log data, the possible effects of elevated temperature and pressure on petrophysical properties should be considered.

V. CLASSIFICATION ACCORDING TO FLUID CHEMISTRY

The chemistry of geothermal fluids can vary extensively from field to field, from well to well in the same field, or from one zone to another in the same well. For example, the total dissolved solids (TDS) content can vary from a few hundred parts per million to over 300 000 ppm. For example, the geothermal reservoir at Mountain Home, Idaho has a TDS of 300 to 800 ppm, which is within the TDS limits of drinking water. The Salton Sea geothermal reservoir has probably the most saline underground water ever discovered: a TDS of over 300 000 ppm, which is close to the saturation level of the dissolved salts at the reservoir temperature.

TDS, or its "sodium chloride (NaCl) equivalent", is not an adequate description of the chemistry of a geothermal fluid, for NaCl is not necessarily the predominant constituent of geothermal waters. Sulfate or bicarbonate may sometimes replace chloride as the predominant anion. Moreover, depending on the geohydrological setting, a geothermal water may contain diverse types of minor constituents. Table 2.2 is a list (from Tsai and others, 1977) of the solid chemical constituents of geothermal waters and the maximum and minimum concentrations reported in the literature. Some of these constituents may have significant effects on well logs. For example, boron and lithium, common in geothermal waters, have high capture cross sections to thermal neutrons. Table 2.3 is a similar list of dissolved gases in geothermal waters. Table 2.4 from the same reference lists the major (defined as those over 10 000 ppm in concentration), secondary (over 1 000 ppm), minor (over 1 ppm) and trace (less than 0.01 ppm) constituents of geothermal waters. Detailed chemical analysis of geothermal waters is not always available, but the TDS is. Hence, TDS has been used to classify geothermal reservoirs as shown in Table 2.1.

Electrical resistivity logs are affected by the chemistry of the fluid because the chemistry determines the resistivity of the formation water. This is important if one wants to estimate formation water salinity from well logs, where usually the dissolved solids are taken to be NaCl. Both SP and a combination of R_t and R_{xo} tools can be used to estimate "NaCl equivalent" salinities of geothermal waters.

As formation water salinity decreases, the conductivity of the water decreases and consequently the conductivities of the clay minerals or metallic minerals become more significant relative to the overall formation conductivity. Hence, formation resistivity factors calculated from well logs are likely to be too high for such reservoirs, and consequently the calculated cementation factor is likely to be too low. For many low salinity geothermal systems, the resistivity of the mud filtrate is close or even less than that of the formation water. This causes small or positive SP deflections.

FREQUENCY OF OCCURRENCE OF RESERVOIR TYPES

It is worthwhile at this point to check the frequency of occurrence of the various reservoir types listed in Table 2.1. Most of the well-known geothermal reservoirs in the Univted States were designated a type according to each of the classification schemes proposed in Table 2.1. In Table 2.5, we have shown the typing of twenty-six such well-known geothermal reservoirs. In Table 2.5, a type IA implies a steam reservoir, IB a high-temperature water reservoir, and so on. A type IIA/B means both type IIA and IIB lithologies are present in the reservoir. A part of Task 2 calls for typing all KGRA's (Known Geothermal Resources Areas) according to these classification schemes. Unfortunately, data are too scanty to allow reliable typing of the reservoirs other than those listed in Table 2.5. We are searching the literature to obtain as much of the needed information as possible.

Although the group of reservoirs shown in Table 2.5 is a statistically small sample (26 reservoirs as compared to 297 identified ones), it includes most of the reservoirs under active development. Based on this sample, we can calculate the frequency of occurrences of the various reservoir types in the United States. This can be done by counting (from Table 2.5) the number of reservoirs belonging to a certain class and then calculating the percentage frequency of occurrence of this class compared to the other classes in the same classification scheme. For example, if there are 100 reservoirs of Type IV of which 30 are of Type IVB, then the frequency of occurrence of Type IVB reservoir is 30 percent.

Table 2.6 shows the computed frequencies of occurrence of the reservoir types under each classification scheme proposed in Table 2.1. We are attempting to prepare such a frequency table including all KGRA's. A few tentative conclusions can be drawn (about reservoirs under current development) from Table 2.6.

1. Hot water reservoirs are far more frequent than steam or dry reservoirs.

2. Besides breccia and metamorphic lithology, all other lithologies have similar frequencies of occurrence.

3. Basin & Range province has the most numerous hydrothermal geothermal sites. This province, together with the Northwest Volcanic and Salton Trough provinces contain the bulk of the hydrothermal reservoirs.

4. Fracture type is the most common pore geometry.

5. Low-Salinity reservoirs are the most frequent.

Obviously such conclusions will be statistically significant when we include all KGRA's as in Figure 2.1. Such conclusions will help us to decide the priority to be attached to developing log analysis techniques for each reservoir type.

TABLE 2.2

CHEMICAL COMPOSITION OF GEOTHERMAL WATERS
(FROM TSAI et al., 1977)

Constituent	Concentration in ppm
Aluminum (Al)	0 - 7 140
Ammonium (NH_4)	0 - 1 400
Arsenic (As)	0 - 12
Barium (Ba)	0 - 250
Boron (B)	0 - 1 200
(HBO_2)	13.6 - 4 800
Bromide (Br)	0.1 - 3 030
Cadmium (Cd)	0 - 1
Calcium (Ca)	0 - 62 900
Carbon Dioxide (CO_2)	0 - 490
(HCO_3)	0 - 10 150
(CO_3)	0 - 1 653
(HCO_3 + CO_3)	20 - 1 000
(CO_2 + HCO_3 + CO_3)	15 - 7 100
Cesium (Cs)	0.002 - 22
Chloride (Cl)	0 - 241 000
Cobalt (Co)	0.014 - 0.018
Copper (Cu)	0 - 10
Fluoride (F)	0 - 35
Germanium (Ge)	0.037 - 0.068
Hydrogen Sulfide (H_2S, total)	0.2 - 74

Chemical Composition of Geothermal Waters, cont'd.

Constituent	Concentration in ppm
Iodide (I)	0 - 105
Iron (Fe)	0 - 4 200
Lanthanum (La)	20
Lead (Pb)	0 - 200
Lithium (Li)	0 - 300
Magnesium (Mg)	0 - 39 200
Manganese (Mn)	0 - 2 000
Mercury (Hg)	0 - 10
Molybdenum (Mo)	0.029- 0.074
Nickel (Ni)	0.005 - 2
Nitrate (NO_3)	0 - 35
Nitrite (NO_2)	0 - 1
Oxygen (O_2, dissolved)	0 - 10
Phosphate (PO_4)	0 - 0.3
(HPO_4)	0.75 - 2.05
(H_2PO_4)	0.02 - 0.22
Potassium (K)	0.6 - 29 900
Rubidium (Rb)	0 - 169
Silica (SiO_2, total)	3 - 1 441
Silver (Ag)	0 - 2
Sodium (Na)	2 - 79 800
Strontium (Sr)	0.133 - 2 000
Sulfate (SO_4)	0 - 84 000

Chemical Composition of Geothermal Waters, cont'd

Constitutent	Concentration in ppm
Sulfur (S)	0-30
Total Dissolved Salts	47 - 387 500
Zinc (Zn)	0.004 - 970
Zirconium (Zr)	24

The following are trace elements found at Sinclair #4 well, Salton Sea, California

Antimony (Sb), Beryllium (Be), Bismuth (Bi), Cerium (Ce), Dysprosium (Dy), Erbium (Er), Europium (Eu), Gadolinium (Gd), Gallium (Ga), Gold (Au), Hafnium (Hf), Holmium (Ho), Indium (In), Iridium (Ir), Lutetium (Lu), Neodymium (Nd), Niobium (Nb), Osmium (Os), Palladium (Pd), Platinum (Pt), Praseodymium (Pr), Rhenium (Re), Rhodium (Rh), Ruthenium (Ru), Samarium (Sm), Scandium (Sc), Selenium (Se), Tantalum (Ta), Tellurium (Te), Terbium (Tb), Thallium (Tl), Thorium (Th), Thulium (Tm), Titanium (Ti), Tungsten (W), Uranium (U), Vanadium (V), Ytterbium (Yb), Yttrium (Y).

TABLE 2.3

GAS COMPOSITION OF GEOTHERMAL VAPORS
(FROM TSAI et al., 1977)

Constituent	Concentration in volume percent
Ammonia (NH_3)	0 - 5.36%
Argon (Ar)	0 - 6.3
Arsenic (As)	0.002 - 0.05
Boric Acid (H_3BO_3)	0 - 0.45
Carbon Dioxide (CO_2)	0 - 99
Carbon Monoxide (CO)	0 - 3
Helium (He)	0 - 0.3
Hydrocarbon C_2 and greater	0 - 18.3
Hydrogen (H_2)	0 - 39
Hydrogen Fluoride (HF)	0.00002
Hydrogen Sulfide (H_2S)	0 - 42
(H_2 + H_2S)	0.2 - 6
Mercury (Hg)	0.007 - 40.7 (ppb)
Methane (CH_4)	0 - 99.8
Nitrogen (N_2)	0 - 97.1
(N_2 + Ar)	0.6 - 96.2
Oxygen (O_2)	0 - 64
Sulfur Dioxide (SO_2)	0 - 31

TABLE 2.4

RELATIVE ABUNDANCE OF CHEMICAL COMPOSITION IN GEOTHERMAL WATERS
(FROM TSAI etal., 1977)

Major Constituents (maximum>10 000ppm)	Secondary Constituents (maximum>1 000ppm)	Minor Constituents (maximum>1ppm)	Trace Constituents (generally<0.01ppm)	
Chloride	Aluminum	Arsenic	Antimony	Platinum
Sulfate	Iron	Barium	Beryllium	Praseodymium
Sodium	Bromide	Cadmium	Bismuth	Rhenium
Calcium	Manganese	Cesium	Cerium	Rhodium
Magnesium	Strontium	Copper	Dysprosium	Ruthenium
Potassium	Carbonate	Fluoride	Erbium	Samarium
Bicarbonate	Silica (total)	Hydrogen Sulfide(total)	Europium	Scandium
	Ammonium	Iodide	Gadolinium	Selenium
	Boron	Lanthanum	Gallium	Tantalum
		Lead	Germanium	Tellurium
		Lithium	Gold	Terbium
		Mercury	Hafnium	Thallium
		Nickel	Holmium	Thorium
		Nitrate	Indium	Thulium
		Phosphate(total)	Iridium	Titanium
		Rubidium	L utetium	Tungsten
		Silver	Molybdenum	Uranium
		Zinc	Neodymium	Vanadium
		Zirconium	Niobium	Ytterbium
			Osmium	Yttrium
			Palladium	

TABLE 2.5
TYPING OF WELL-KNOWN GEOTHERMAL RESERVOIRS
(according to Classification Schemes in Table 2.1)

RESERVOIR	LOCATION	TYPE
Salton Sea	Imperial Co., California	IB, IIA/F, IIIC, IVA/B, VD
Brawley	Imperial Co., California	IB, IIA, IIIC, IVA, VC
Heber	Imperial Co., California	IC, IIA, IIIC, IVA, VB
East Mesa	Imperial Co., California	IC, IIA, IIIC, IVA, VB
Dunes	Imperial Co., California	ID, IIA, IIIC, IVA, VB
Cerro Prieto	Baja California, Mexico	IB, IIA, IIIC, IVA, VB
The Geysers	Sonoma Co., California	IA, IIB, IIID, IVB, VA
Coso Hot Springs	Inyo Co., California	IC, IIB/C, IIIAC, IVB, VB
Long Valley	Mono Co., California	IC, IIC/D, IIIAc, IVB, VA
Surprise Valley	Modoc Co., California	IC, IIA/C/D, IIIAc/Bb, VA
Clear Lake	Lake County, California	IC, IIB/F, IID, IVB, VA
Kilauea	Hawaii	IB, IIC/F, IIIF, IVB/C, VA
Bruneau-Grand View	Owyhee Co., Idaho	ID, IIA/C/D, IIIBa, IVA/C, VA
Raft River	Cassia Co., Idaho	ID, IIA/C/D, IIIBa, IVA, VA
Mountain Home	Elmore Co., Idaho	IC, IIC/D, IIBa, IVB/C, VA
Yellowstone	Park Co., Wyoming	IA/B, IIC/D/F, IIIBc, IVB/C, VA
Roosevelt Hot Springs	Beaver Co., Utah	IB, IIC, IIIAa, IVB,VB
Brigham City	Utah	ID
Valles Caldera	Sandoval Co., New Mexico	IB, IIC/F, IIIE, IVB, VB
Fenton Hill	Sandoval Co., New Mexico	IE, IIC/F, IIIE, IVB, VE
Chandler	Arizona	IC, VC
Brady's Hot Springs	Lyon/Churchill Co., Nevada	IB, IIA/C/D/F, IIIAc, IVA/B, VA
Steamboat Springs	Washoe Co., Nevada	IC, IIC/D/F, IIIAc, IVB/C, VA
Beowawe	Lander/Eureka Co., Nevada	IB, IIC/D/F, IIIAb, IVB, VA
Fly Ranch	Nevada	ID
Klamath Falls	Oregon	ID

TABLE-2.6
DISTRIBUTION OF GEOTHERMAL RESERVOIRS

I. ACCORDING TO FLUID PHASE & TEMPERATURE

Type	Description	Frequency of Occurrence
IA	Steam	7.4%
IB	High-Temperature Water >204°C (400°F)	33.3%
IC	Moderate-Temperature Water 149-204°C (300-400°F)	33.3%
ID	Low-Temperature Water <149°C (300°F)	22.3%
IE	Dry	3.7%

II. ACCORDING TO LITHOLOGIC TYPES

Type	Description	Frequency of Occurrence
IIA	Sedimentary	22.2%
IIB	Metamorphic	6.7%
IIC	Igneous (Crystalline & Glassy)	31.1%
IID	Volcanic Ash and associated sediments	20.0%
IIE	Breccia	--
IIF	Hydrothermally altered	20.0%

TABLE-2.6 (Continued)

III. ACCORDING TO GEOLOGIC PROVINCE

Type	Description	Frequency of Occurrence
IIIA	Basin & Range	38.5%
IIIB	Northwest Volcanic	19.2%
IIIC	Salton Trough	23.0%
IIID	Northern California Coast Range	7.7%
IIIE	Rio Grand Rift & Colorado Plateau Borderland	7.7%
IIIF	Hawaii	3.9%
IIIG	Alaska	

IV. ACCORDING TO PORE GEOMETRY

Type	Description	Frequency of Occurrence
IVA	Sedimentary Intergranular	31.3%
IVB	Fracture	50.0%
IVC	Vesicular or Vuggy	18.7%

V. ACCORDING TO SALINITY

Type	Description	Frequency of Operation
VA	Low Salinity (<5000 ppm)	52.1%
VB	Moderate Salinity (5000-35000 ppm)	30.4%
VC	High Salinity (35000-100000 ppm)	8.7%
VD	Hyper Saline (>1000000 ppm)	4.4%
VE	Dry	4.4%

REFERENCES

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TASK-3: DATA ACQUISITION

The interpretation of well logs in complex formations requires a great deal of data. After reliable techniques have been developed, less information may be needed to provide answers to some of the problems. A Criterion for Log Selection was established to select wells for initial study and model development.

A. Criterion for Log Selection

A. Logging Suites
   1. Clastics
      a. Resistivity and SP
      b. Porosity/Lithology logs
         Best: Density/Neutron/Sonic/Gamma Ray/Caliper
         or Density/Neutron/Gamma Ray/Caliper
         or Density/Sonic/Gamma Ray/Caliper
      c. Temperature and/or Pressure data
   2. Other Lithologies
      a. Resistivity and SP
      b. Porosity/Lithology logs
         Density/Neutron/Sonic/Gamma Ray/Caliper
      c. Temperature and/or Pressure data.

B. Quality
   1. Properly calibrated
   2. Repeatable
   3. Reasonable hole conditions (Minimum of hole wash-outs and borehole rugosity)
   4. Overlaps of previous runs (when applicable)

C. Auxiliary Logs and Data (no priority order)
   1. Sample Descriptions
   2. Drilling record
   3. Core and Core Analysis
   4. Temperature logs

5. Pressure surveys
6. Production test results
7. Spectral Gamma Ray (K, U, Th)
8. Acoustic Wave

Fields with the most complete data available for study are from

1. East Mesa (California)
2. Raft River (Idaho)
3. Fenton Hill (HDR Project, LASL, New Mexico)

The following catalog lists well logs currently available for study.

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: IE,IIC/F,IIIE,IVB,VE

PAGE 1 OF 3

COMPANY: LOS ALAMOS SCIENTIFIC LAB

WELL: GT #2

FIELD: FENTON HILL

COUNTY: SANDOVAL

STATE: NEW MEXICO

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
3-5-74	ELECTRIC LOG	1	B	1810	150
3-5-74	GAMMA RAY - CALIPER	1/1	B	1807	10
3-5-74	3-D VELOCITY (9')	2	B	1803	50
3-5-74	TEMPERATURE	1	B	1804	50
4-7-74	TEMPERATURE	2	B	2450	30
4-7-74	GAMMA RAY - NEUTRON	2/1	B	2489	0
4-7-74	3-D VELOCITY (BOND LOG)	1	B	2490	50
4-7-74	DENSITY	1	B	2496	0
4-23-74	GAMMA RAY	1	G.O.	3529	1700
4-23-74	CALIPER	1	G.O.	3520	50
4-23-74	DIFF. TEMPERATURE	1	G.O.	3527	200
5-14-74	INDUCTION - ELECTRICAL	1	S.W.S.	3709	2536
5-14-74	COMPENSATED FORMATION DENSITY	1	S.W.S.	3709	2536
5-14-74	BOREHOLE COMPENSATED SONIC	1	S.W.S.	3700	2536
6-5-74	CALIPER	2	B	4272	2400
6-6-74	3-D VELOCITY (6')	3	B	4264	2500
6-6-74	3-D VELOCITY (9')	4	B	4264	2500

GEOTHERMAL WELL LOG CATALOG

COMPANY: LOS ALAMOS SCIENTIFIC LAB
WELL: GT #2
FIELD: FENTON HILL
COUNTY: SANDOVAL
STATE: NEW MEXICO
TIGHT HOLE: NO [X] YES [ ]
CLASSIFICATION:

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
6-6-74	DENSITY	2	B	4272	2510
6-6-74	GAMMA RAY - NEUTRON	3/2	B	4263	2370
6-27-74	GAMMA RAY - NEUTRON	4/3	B	5492	2500
6-27-74	ELECTRIC LOG	3	B	5492	2530
6-27-74	TEMPERATURE	9	B	5494	2500
6-27-74	CALIPER	4	B	5494	2500
7-11-74	TEMPERATURE	10	B	6354	2530
7-12-74	DENSITY	3	B	6350	4000
7-12-74	3-D VELOCITY (9')	6	B	6340	4000
7-12-74	CALIPER	6	B	6350	2500
7-12-74	MICRO - CONTACT	1	B	6350	2530
7-13-74	GAMMA RAY - NEUTRON	5/4	B	6350	5300
9-8-74	SIDEWALL NEUTRON	1	D.A.	6669	5900
9-8-74	DIFF. TEMPERATURE	1	D.A.	6674	0
9-8-74	INDUCTION - ELECTRICAL	2	S.W.S.	6672	6250
9-8-74	COMPENSATED NEUTRON-FORMATION DENSITY	2	S.W.S.	6674	6250
9-8-74	BOREHOLE COMPENSATED SONIC	2	S.W.S.	6673	2536

GEOTHERMAL WELL LOG CATALOG

COMPANY: LOS ALAMOS SCIENTIFIC LAB

WELL: GT #2

FIELD: FENTON HILL

COUNTY: SANDOVAL

STATE: NEW MEXICO

TIGHT HOLE: NO [X] YES [ ]

CLASSIFICATION

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
9-8-74	TEMPERATURE	2	S.W.S.	6678	0
12-10-74	ACOUSTILOG	1	D.A.	9615	6500
12-10-74	ELECTROLOG	1	D.A.	9618	6500
12-10-74	CEMENT BOND LOG - VDL	1	D.A.	9620	8970
12-10-74	DENSILOG	1	D.A.	9618	6500
12-10-74	SPECTRALOG	1	D.A.	9364	2550
12-12-74	DIFF. TEMPERATURE	1	D.A.	9620	6000
12-12-74	CEMENT BOND LOG - VDL	1	D.A.	9590	8900
12-17-74	MINILOG	1	D.A.	8950	5750
12-17-74	SIDEWALL NEUTRON	1	D.A.	8980	5800

GEOTHERMAL WELL LOG CATALOG

COMPANY: LOS ALAMOS SCIENTIFIC LAB
WELL: EE #1
FIELD: FENTON HILL
COUNTY: SANDOVAL
STATE: NEW MEXICO
TIGHT HOLE: NO [X] YES [ ]
CLASSIFICATION: IE,IIC/F,IIIE,IVB,VE
PAGE 1 OF 2

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
6-10-75	ELECTRIC LOG	1	B	1652	550
6-10-75	GAMMA RAY - CALIPER	1	B	1655	490
6-10-75	3-D VELOCITY (6')	1	B	1645	450
6-10-75	3-D VELOCITY (3')	2	B	1645	450
8-9-75	LATEROLOG	1	D.A.	6415	2431
8-9-75	DENSILOG	1	D.A.	6418	2432
8-9-75	ACOUSTILOG	1	D.A.	6407	2432
8-12-75	SPECTRALOG	1	D.A.	6424	2300
8-12-75	CALIPER	1	D.A.	6418	2432
8-11-75	DENSITY	1	B	4860	2400
8-11-75	3-D VELOCITY (3')	1	B	6418	1610
8-11-75	3-D VELOCITY (6')	2	B	6418	1610
8-11-75	CALIPER	1	B	6380	2300
8-11-75	CALIPER	2	B	6380	2400
8-22-75	CEMENT BOND LOG	1	S.W.S.	6420	4400
8-26-75	TEMPERATURE	1	S.W.S.	6879	
8-26-75	INDUCTION - ELECTRICAL	1		6873	6424

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION

COMPANY: LOS ALAMOS SCIENTIFIC LAB

WELL: EE #1

FIELD: FENTON HILL

COUNTY: SANDOVAL

STATE: NEW MEXICO

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
9-25-75	ACOUSTILOG	2	D.A.	9558	6417
9-27-75	CALIPER (4 ARM)	2	D.A.	9560	6413
9-28-75	DENSILOG	2	D.A.	9570	6420
9-28-75	LATEROLOG	2	D.A.	9567	6414
9-28-75	CEMENT BOND LOG - VDL	2	D.A.	9572	6320
10-27-75	CEMENT BOND LOG - VDL	3	D.A.	9968	7500

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: IE,IIC/F,IIIE,IVB,VE

PAGE 1 OF 1

COMPANY: L.A.S.L. (Roberts Drilling Co.)

WELL: JEMEZ GRANITE NO. 1

FIELD: JEMEZ PLATEAU

COUNTY: SANDOVAL

STATE: NEW MEXICO

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
5-13-72	TEMPERATURE	1	S.W.S.	526	70
5-13-72	COMPENSATED FORMATION DENSITY	1	S.W.S.	526	0
5-23-72	INDUCTION - ELECTRICAL	1	S.W.S.	1531	1357
5-23-72	COMPENSATED FORMATION DENSITY	2	S.W.S.	1532	1357
5-23-72	COMPENSATED NEUTRON	1	S.W.S.	1532	1357
6-29-72	GAMMA RAY	1	B	2574	0
6-29-72	GAMMA RAY	2	B	2574	2000
6-30-72	CALIPER	1	B	2574	0
6-30-72	TEMPERATURE	1	B	2575	0
6-30-72	DENSITY	1	B	2574	2350
6-30-72	3-D VELOCITY LOG	1	B	2575	2300
6-30-72	3-D VELOCITY LOG	2	B	2575	2300
6-30-72	3-D VELOCITY LOG	3	B	2567	2320
6-30-72	3-D VELOCITY LOG	4	B	2567	2320
6-30-72	SEISVIEWER	1	B	2575	2390
6-30-72	3-D VELOCITY LOG	5,6,7	B	2563	2380
2-21-73	SEISVIEWER	2	B	2575	2390
2-15-73	TEMPERATURE	2,3	B	2474	0
2-16-73				2576	250

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: IC,IIA,IIC,IVA,VB

COMPANY: SARDI OIL COMPANY

WELL: SARDI NO. 1

FIELD: CALIPATRIA

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
12-3-60	ELECTRICAL LOG	1	S.W.S.	4603	312
12-11-60	ELECTRICAL LOG	2	S.W.S	5617	4603
12-16-60	SONIC LOG	1	S.W.S.	5453	312

GEOTHERMAL WELL LOG CATALOG

COMPANY: J.I. O'NEILL, GEOTHERMAL, INC.

CLASSIFICATION: IC,IIA,IIIC,IVA,VB

PAGE 1 OF 1

WELL: I.I.D. NO. 1

FIELD: NILAND

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
2-18-62	ELECTRICAL LOG	1	S.W.S.	5234	1624
2-23-62	TEMPERATURE	1	S.W.S.	2840	100
2-18-62	GAMMA RAY - NEUTRON	1	S.W.S.	1701	64

GEOTHERMAL WELL LOG CATALOG

COMPANY: WESTERN GEOTHERMAL, INC.

CLASSIFICATION: IC,IIA,IIIC,IVA,VB

WELL: SINCLAIR NO. 3

FIELD: CALIPATRIA

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
12-1-62	INDUCTION - ELECTRICAL LOG	1	S.W.S.	5329	1365
12-1-62	SONIC LOG	1	S.W.S.	5325	3300
12-1-62	TEMPERATURE	1	S.W.S.	5324	1450

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: IC,IIA,IIIC,IVA,VB

PAGE 1 OF 1

COMPANY: SHELL OIL COMPANY

WELL: IMPERIAL IRRIGATION DIST. #2

FIELD: NILAND

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
11-26-63	INDUCTION - ELECTRICAL LOG	1	S.W.S.	1597	100
12-3-63	INDUCTION - ELECTRICAL LOG	2	S.W.S.	3658	1598
12-14-63	INDUCTION - ELECTRICAL LOG	3	S.W.S.	5081	3658
12-21-63	INDUCTION - ELECTRICAL LOG	4	S.W.S.	5826	5081
2-22-64	TEMPERATURE	1	S.W.S.	4500	100
2-26-64	GAMMA RAY - NEUTRON	2	S.W.S.	5291	150
2-26-64	CEMENT BOND LOG	1	S.W.S.	5200	200
3-19-64	CONTINUOUS FLOWMETER	1	S.W.S.	3840	200

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION

PAGE 1 OF 1

COMPANY: GEOTHERMAL POWER COMPANY

WELL: KELLY HOT SPRINGS #1

FIELD: CANBY

COUNTY: MODOC

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
7-13-74	INDUCTION - ELECTRICAL LOG	1	S.W.S.	3372	547
7-13-74	BOREHOLE COMPENSATED SONIC	1	S.W.S.	3371	547
7-13-74	COMPENSATED FORMATION DENSITY	1	S.W.S.	3372	547
7-13-74	TEMPERATURE	1	S.W.S.	3370	70
7-13-74	TEMPERATURE	2	S.W.S.	3370	100
7-14-74	TEMPERATURE	3	S.W.S.	3370	360

GEOTHERMAL WELL LOG CATALOG

COMPANY: AEROJET NUCLEAR - INEL

WELL: RRGE #1

COUNTY: CASSIA

STATE: IDAHO

FIELD: RAFT RIVER GEOTHERMAL

TIGHT HOLE: NO [X] YES [ ]

CLASSIFICATION: ID,IIA/C/D,IIIBa,IVA,VA

PAGE 1 OF 1

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
1-9-75	DUAL INDUCTION - LATEROLOG	1	S.W.S.	894	33
2-2-75	DUAL INDUCTION - LATEROLOG	2	S.W.S.	4612	888
1-9-75	BOREHOLE COMPENSATED SONIC	1	S.W.S.	896	30
2-2-75	BOREHOLE COMPENSATED SONIC	2	S.W.S.	4618	880
4-6-75	BOREHOLE COMPENSATED SONIC	3	S.W.S.	4998	3592
2-2-75	COMPENSATED NEUTRON-FORMATION DENSITY	1	S.W.S.	4619	880
4-6-75	COMPENSATED NEUTRON-FORMATION DNESITY	2	S.W.S.	4992	2692
1-9-75	CALIPER (4 ARM)	1	S.W.S.	898	18
2-2-75	CALIPER (4 ARM)	2	S.W.S.	4619	870
2-9-75	CALIPER (4 ARM)	3	S.W.S.	4616	900
4-6-75	CALIPER (4 ARM)	4	S.W.S.	5002	3000
4-6-75	CEMENT BOND LOG	1	S.W.S.	3650	2700
2-10-75 2-2-75	TEMPERATURE	1-16	S.W.S.	4630	900
4-6-75		17,18	S.W.S.	5000	900

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: ID,IIA/C/D,IIIBa,IVA,VA

PAGE 1 OF 1

COMPANY: E.G. & G. OF IDAHO

WELL: RRGI #4

FIELD: RAFT RIVER GEOTHERMAL

COUNTY: CASSIA

STATE: IDAHO

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
4-15-77	DUAL INDUCTION - FOCUSED LOG	1	D.A.	1886	403
4-16-77	ACOUSTILOG	1	D.A.	1901	401
4-16-77	DENSILOG	1	D.A.	1908	400
4-17-77	COMPENSATED NEUTRON	1	D.A.	1908	401

GEOTHERMAL WELL LOG CATALOG

COMPANY: AEROJET NUCLEAR INEL

CLASSIFICATION: ID,IIA/C/D,IIIBa,IVA,VA

WELL: RRGE #3

FIELD: RAFT RIVER GEOTHERMAL

COUNTY: CASSIA

STATE: IDAHO

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
3-30-76	DUAL INDUCTION - FOCUSED LOG	1	D.A.	1410	140
4-17-76	DUAL INDUCTION - FOCUSED LOG	2	D.A.	4209	1390
5-2-76	DUAL INDUCTION - FOCUSED LOG	3	D.A.	5863	4247
4-17-76	COMPENSATED NEUTRON	2	D.A.	4208	1385
5-1-76	COMPENSATED NEUTRON	3	D.A.	5863	4200
4-18-76	ACOUSTILOG	2	D.A.	4201	1385
5-1-76	ACOUSTILOG	3	D.A.	5856	4247
3-30-76	CALIPER	1	D.A.	1409	54
4-17-76	CALIPER	2	D.A.	4209	1385
4-20-76	ACOUSTIC CEMENT BOND LOG	1	D.A.	2393	1206
3-30-76	TEMPERATURE	1	D.A.	1412	25
5-1-76	TEMPERATURE	2	D.A.	5868	SURF
5-3-76	TEMPERATURE	3	D.A.	5865	SURF

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: ID,IIA/C/D,IIIBa,IVA,VA

COMPANY: E.G. & G. IDAHO, INC.

WELL: RRGE #3

FIELD:

COUNTY: CASSIA

STATE: IDAHO

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
4-17-77	DUAL INDUCTION - FOCUSED LOG	1	D.A.	5953	4245
4-18-77	DENSILOG	1	D.A.	5931	4245
4-17-77	ACOUSTILOG	1	D.A.	5924	4244
4-18-77	COMPENSATED NEUTRON	1	D.A.	5932	4244
4-15-77	TEMPERATURE	4	D.A.	5917	4100

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: ID,IIA/C/D,IIIBa,IVA,VA

COMPANY: REYNOLDS ELECTRIC COMPANY & AEROJET NUCLEAR COMPANY

WELL: RRGE #2

FIELD: RAFT RIVER GEOTHERMAL

COUNTY: CASSIA

STATE: IDAHO

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
6-27-75	DUAL INDUCTION - LATEROLOG	1	S.W.S.	5998	4215
5-13-75	COMPENSATED NEUTRON-FORMATION DENSITY	1	S.W.S.	4227	870
6-27-75	COMPENSATED NEUTRON-FORMATION DENSITY	2	S.W.S.	6003	4220
6-27-75	BOREHOLE COMPENSATED SONIC LOG	2	S.W.S.	5997	4219
6-27-75	TEMPERATURE LOG	2	S.W.S.	6004	4220
5-12-75	TEMPERATURE LOG	1	S.W.S.	4228	780
5-21-75	3-D BOND	1	B	1300	30
5-21-75	CALIPER	2	B	4224	850
6-3-75	ACOUSTIC BOND LOG	1	D.A.	4200	0
6(4-9)-75	ACOUSTIC BOND LOG (SQUEEZE)	2	D.A.	1500	50
6-12-75	ACOUSTIC BOND LOG	3	D.A.	1532	0

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: IC,IIA,IIIC,IVA,VB

COMPANY: REPUBLIC GEOTHERMAL, INC.

WELL: EAST MESA 78-30

FIELD: EAST MESA

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
6-24-77	DUAL INDUCTION - LATEROLOG	1	S.W.S.	1483	100
7-3-77	DUAL INDUCTION - LATEROLOG	2	S.W.S.	5286	1490
7-15-77	DUAL INDUCTION - LATEROLOG	3	S.W.S.	7451	5284
7-3-77	BOREHOLE COMPENSATED SONIC	1	S.W.S.	5190	1490
7-3-77	COMPENSATED NEUTRON-FORMATION DENSITY	1	S.W.S.	5292	1490
7-15-77	COMPENSATED NEUTRON-FORMATION DENSITY	2	S.W.S.	7456	5286
	COMPUTER PROCESSED INTERPRETATION	1	S.W.S.	5250	1500
	(CORIBAND)				
	COMPUTER PROCESSED INTERPRETATION	2	S.W.S.	7430	5290
	(CORIBAND)				

GEOTHERMAL WELL LOG CATALOG

COMPANY: REPUBLIC GEOTHERMAL, INC.
CLASSIFICATION: IC,IIA,IIIC,IVA,VB
WELL: EAST MESA 16-30
FIELD: EAST MESA
COUNTY: IMPERIAL
STATE: CALIFORNIA
TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
6-10-77	DUAL INDUCTION - LATEROLOG	1	S.W.S.	1493	106
6-19-77	INDUCTION - GAMMA RAY	2	S.W.S.	5909	1488
6-27-77	INDUCTION	3	S.W.S.	7999	5912
6-20-77	BOREHOLE COMPENSATED SONIC	1	S.W.S.	5911	2000
6-27-77	BOREHOLE COMPENSATED SONIC	2	S.W.S.	7910	5912
6-19-77	COMPENSATED NEUTRON-FORMATION DENSITY	1	S.W.S.	5914	2000
6-27-77	COMPENSATED NEUTRON-FORMATION DENSITY	2	S.W.S.	8004	5912
	COMPUTER PROCESSED INTERPRETATION	1	S.W.S.	5880	2000
	(CORIBAND)				
	COMPUTER PROCESSED INTERPRETATION	2	S.W.S.	7975	5915
	(CORIBAND)				

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: IC,IIA,IIIC,IVA,VB

PAGE 1 OF 1

COMPANY: REPUBLIC GEOTHERMAL, INC.

WELL: EAST MESA 56-30

FIELD: EAST MESA

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
5-9-77	DUAL INDUCTION - LATEROLOG	1	S.W.S.	1506	96
5-15-77	DUAL INDUCTION - LATEROLOG	2	S.W.S.	5318	1503
5-31-77	DUAL INDUCTION - LATEROLOG	3	S.W.S.	7521	5328
6-1-77	BOREHOLE COMPENSATED SONIC	1	S.W.S.	7520	5329
5-15-77	COMPENSATED NEUTRON-FORMATION DENSITY	1	S.W.S.	5310	1504
5-31-77	COMPENSATED NEUTRON-FORMATION DENSITY	2	S.W.S.	7524	5329
	COMPUTER PROCESSED INTERPRETATION	1	S.W.S.	5310	1510
	(CORIBAND)				
	COMPUTER PROCESSED INTERPRETATION	2	S.W.S.	7510	5332
	(CORIBAND)				

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: IC,IIA,IIIC,IVA,VB

PAGE 1 OF 1

COMPANY: REPUBLIC GEOTHERMAL, INC.

WELL: EAST MESA 52-29

FIELD: EAST MESA

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
12-4-77	DUAL INDUCTION - LATEROLOG	1	S.W.S.	2504	90
12-12-77	DUAL INDUCTION - LATEROLOG	2	S.W.S.	4523	2476
12-12-77	BOREHOLE COMPENSATED SONIC	1	S.W.S.	4524	2476
12-12-77	COMPENSATED NEUTRON-FORMATION DENSITY	1	S.W.S.	4526	2476
	COMPUTER PROCESSED INTERPRETATION (CORIBAND)	1	S.W.S.	4500	2480

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: IC,IIA,IIIC,IVA,VB

PAGE 1 OF 1

COMPANY: REPUBLIC GEOTHERMAL, INC.

WELL: EAST MESA 18-28

FIELD: EAST MESA

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
12-13-75	DUAL INDUCTION - LATEROLOG	1	S.W.S.	1287	61
1-13-76	DUAL INDUCTION - LATEROLOG	2	S.W.S.	5016	1288
1-23-76	DUAL INDUCTION - LATEROLOG	3	S.W.S.	7998	5018
1-23-76	COMPENSATED NEUTRON-FORMATION DENSITY	1	S.W.S.	8001	5018
1-13-76	CALIPER (4 ARM)	1	S.W.S.	5012	1287
1-23-76	TEMPERATURE	1	S.W.S.	8002	5000
5-19-76	GAMMA RAY (PDC)	1	S.W.S.	6400	5900
	COMPUTER PROCESSED INTERPRETATION (SARABAND)	2	S.W.S.	7980	5020

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: IC,IIA,IIIC,IVA,VB

PAGE 1 OF 1

COMPANY: REPUBLIC GEOTHERMAL, INC.

WELL: 38-30

FIELD: EAST MESA

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
9-26-75	DUAL INDUCTION - LATEROLOG	1	S.W.S.	1225	100
10-9-75	DUAL INDUCTION - LATEROLOG	2	S.W.S.	5678	1199
10-23-75	DUAL INDUCTION - LATEROLOG	3	S.W.S.	8964	5103
10-9-75	COMPENSATED NEUTRON-FORMATION DENSITY	1	S.W.S.	5679	1194
10-23-75	COMPENSATED NEUTRON-FORMATION DENSITY	2	S.W.S.	8966	5103
	COMPUTER PROCESSED INTERPRETATION (SARABAND)	1	S.W.S.	5668	1204
	COMPUTER PROCESSED INTERPRETATION (SARABAND)	2	S.W.S.	8930	5480
	COMPUTER PROCESSED INTERPRETATION (SARABAND)	3	S.W.S.	5000	3800

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: IC,IIA,IIIC,IVA,VB

PAGE 1 OF 1

COMPANY: REPUBLIC GEOTHERMAL, INC.

WELL: 16-29

FIELD: EAST MESA

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
11-4-75	DUAL INDUCTION - LATEROLOG	1	S.W.S.	1132	66
11-16-75	DUAL INDUCTION - LATEROLOG	2	S.W.S.	4656	1092
12-4-75	DUAL INDUCTION - LATEROLOG	3	S.W.S.	7984	4632
12-3-75	COMPENSATED NEUTRON-FORMATION DENSITY	1	S.W.S.	7988	4632
12-3-75	COMPUTER PROCESSED INTERPRETATION (SARABAND)	1	S.W.S.	7960	4662

GEOTHERMAL WELL LOG CATALOG

COMPANY: UNITED STATES BUREAU OF RECLAMATION

CLASSIFICATION: IC,IIA,IIIC,IVA,VB

PAGE 1 OF 1

WELL: MESA 6-2

FIELD: EAST MESA HOLTVILLE

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
8-9-73	DUAL INDUCTION - LATEROLOG	1	S.W.S.	5986	1007
8-9-73	BOREHOLE COMPENSATED SONIC	1	S.W.S.	5996	1008
8-8-73	COMPENSATED NEUTRON-FORMATION DENSITY	1	S.W.S.	6004	1008
8-8-73	HIGH RESOLUTION CONTINUOUS DIPMETER	1	S.W.S.	6004	1008
	DIPMETER COMPUTATION 4' x 4' x 45'	1	S.W.S.	6004	1008

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: IC,IIA,IIC,IVA,VB

PAGE 1 OF 1

COMPANY: BUREAU OF RECLAMATION

WELL: MESA 5-1

FIELD: MESA ANOMALY

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
5-1-74	DUAL INDUCTION - LATEROLOG	1	S.W.S.	6018	1026
5-2-74	BOREHOLE COMPENSATED SONIC LOG	1	S.W.S.	6013	1024
5-2-74	COMPENSATED NEUTRON-FORMATION DENSITY	1	S.W.S.	6024	1027
5-2-74	HIGH RESOLUTION CONTINUOUS DIPMETER	1	S.W.S.	6009	3452
	COMPUTER PROCESSED INTERPRETATION	1	S.W.S.	6006	1060
	(SARABAND)				

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: IC,IIA,IIIC,IVA,VB

PAGE 1 OF 1

COMPANY: U.S. BUREAU OF RECLAMATION

WELL: MESA 31-1

FIELD: MESA ANOMALY

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
6-20-74	DUAL INDUCTION - LATEROLOG	1	S.W.S.	6200	1015
6-20-74	BOREHOLE COMPENSATED SONIC LOGS	1	S.W.S.	6200	1015
6-19-74	COMPENSATED NEUTRON-FORMATION DENSITY	1	S.W.S.	6210	1015
	COMPUTER PROCESSED INTERPRETATION	1	S.W.S.	6186	1020
	(SARABAND)				

GEOTHERMAL WELL LOG CATALOG

COMPANY: U.S. BUREAU OF RECLAMATION

CLASSIFICATION: IC,IIA,IIIC,IVA,VB

PAGE 1 OF 1

WELL: MESA 6-1

FIELD: MESA ANOMALY

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
7-1-72	DUAL INDUCTION - LATEROLOG	1	S.W.S.	2500	378
7-30-72	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	1	S.W.S.	2485	380
	(SARABAND)				
	COMPUTER PROCESSED INTERPRETATION	2	S.W.S.	7290	2510
	(SARABAND)				
	COMPUTER PROCESSED INTERPRETATION	3	S.W.S.	8000	7332
	(SARABAND)				

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: IC,IIA,IIIC,IVA,VB

PAGE 1 OF 1

COMPANY: BUREAU OF RECLAMATION

WELL: MESA 8-1

FIELD: MESA ANOMALY

COUNTY: IMPERIAL

STATE: CALIFORNIA

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
5-25-74	DUAL INDUCTION - LATEROLOG	1	S.W.S.	6199	1000
5-25-74	BOREHOLE COMPENSATED SONIC	1	S.W.S.	6070	1000
5-25-74	COMPENSATED NEUTRON-FORMATION DENSITY	1	S.W.S.	6204	1000
5-27-74	HIGH RESOLUTION CONTINUOUS DIPMETER	1	S.W.S.	6091	1000
	COMPUTER PROCESSED INTERPRETATION	1	S.W.S.	6186	1000
	(SARABAND)				

GEOTHERMAL WELL LOG CATALOG

CLASSIFICATION: IB,IIA,IIIC,IVA,VB

COMPANY: COMISION DE ENERGIA GEOTHERMICA

WELL: M-45

FIELD: CERRO PRIETO

COUNTY: MEXICALI

STATE: BAJA, MEXICO

TIGHT HOLE: NO [X] YES [ ]

DATE	TYPE LOG	RUN #	LOG COMPANY	LOWER RDG	UPPER RDG
4-18-78	INDUCTION - ELECTRICAL LOG	1	S.W.S.	2418	641
6-23-73	DUAL INDUCTION - LATEROLOG	2	S.W.S.	4582	2410
6-23-73	COMPENSATED NEUTRON-FORMATION DENSITY	1	S.W.S.	4594	2407
	SARABAND	1	S.W.S.	4580	2410

NOTES

B. Literature Search

Computerized literature searches were made in various data files. The pertinent references discovered are listed on the following pages. Although all of the listed works do not deal directly in their entirety with log analysis of geothermal well logs, many contain references to valuable information in related fields.

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NOTES

TASK-4: PROBLEM DEFINITION AND DIRECTION FOR SOLUTION

The log analysis, as presented for the GT-2 and RRGE #2 wells, is typical for the state-of-the-art techniques developed within the petroleum industry. Additional processing, particularly Z-plot techniques, extend the ability to resolve lithology definition. For example: spectral gamma-ray data such as the concentrations of potassium, thorium or uranium, or thorium-uranium ratios have been used in Z-plots of the GT-2 well and provided mineralogic trends for syenogranite, monzogranite, biotite, and hornblende (Merkel, 1976). The basic techniques and concepts in use currently can be used for much of the evaluation if a great deal of matrix and log response characteristics are collected and cataloged. The data from tests such as the LASL Hot Dry Rock Project and the Raft River Project are steps in this direction, as reasonably complete logging suites, sample and core data, and production-testing results are available.

The fundamental problems associated with geothermal well log interpretation can be divided into three groups.

1. Lithology and porosity
2. Fracture detection
3. Thermal evaluation

With improved solutions to these fundamental problems, other formation parameters, such as permeability, may be resolved with greater accuracy.

Efforts therefore should be directed to

1. Establishment of matrix and response characteristics for currently available logging tools. In addition, new tools such as the EMP (Electromagnetic

Propagation Tool) should be evaluated for their potential contribution to solving the problems.

2. Evaluate the many techniques for fracture detection and define the best systems of interpretation for application to geothermal wells.

3. Refine the techniques used for determining true reservoir temperature and the heat flow characteristics of formations with various pore structures.

B. Geothermal Test Hole GT-2

The Geothermal Test Hole No. 2 (GT-2) is drilled into Precambrian-age basement granitic rocks of the Jemez Mountains in north-central New Mexico. Drilled by Los Alamos Scientific Laboratory, the well tests the viability of heat extraction by the Hot Dry Rock (HDR) technique (See references, page 112).

The interval selected for study, 1 905 - 2 027m (6 250 - 6 650 ft) is described (Pettitt, 1975; Kintzinger and others, 1977) as predominantly light pink granite and small sections of

Schist; gray with biotite
Gneiss; white with quartz, feldspar
Granite; pink, slightly altered
Granodiorite; pink
Quartz Monzonite; light pink.

Electrical logging for this interval was performed by Schlumberger Well Services and included

1. Dual Induction - Laterolog
2. Compensated Neutron - Formation Density with Gamma Ray and caliper
3. Borehole Compensated Sonic.

In addition, other surveys were performed by Birdwell, Dresser-Atlas and GO Wireline Services over the same depth interval and other portions of the borehole (see listing of logs, Task 3, page 61).

Initial processing of the data by computer was performed in order to determine

1. Lithology
2. Porosity
3. Fracture locations.

Figures 4.1, 4.2, and 4.3 display the neutron, density, and sonic log data in crossplot form (Schlumberger, 1972).

Figure 4.1 is a crossplot of density and neutron values showing the frequency of occurrence of paired values. The area with the greatest frequency of occurrence is blocked in to indicate the trend of data. For reference, the response lines for sandstone (quartz), limestone, and dolomite are shown. The trend indicates that the matrix may be a mixture of quartz and some mineral with a matrix density less than 2.65 g/cm^3, and very low porosity.

Figure 4.2 is a frequency crossplot of neutron and sonic data. The trend is between the reference sandstone and limestone response lines. If a reference sandstone response line is drawn using a matrix velocity of 5.94 km/s (19 500 ft/s) shown as dotted line, instead of 5.49 km/s (18 000 ft/s) as shown with solid line, the data indicate most rock to have acoustical matrix values higher than quartz sandstone.

Figure 4.3 crossplots density and sonic data. This particular crossplot has very poor porosity and lithology resolution in the regions of sandstone, limestone, and dolomite. It is best suited for indications of evaporite minerals (Schlumberger, 1972). If the sandstone response line was adjusted to a matrix velocity of 5.94 km/s (19 500 ft/s) the sandstone and limestone response lines would nearly coincide, but with different porosity values. The trend of data indicates the rock to be lower in density and/or sonic travel times to be much shorter than the quartz sandstone trend. Since the section studied is predominantly light pink granite, the low density and low travel time may be caused by the presence of orthoclase (matrix density of 2.52 g/cm^3 and plagioclase (travel time = 164 µs/m (50 µs/ft)) feldspar respectively.

Figure 4.4 is a crossplot of M and N values (Schlumberger, 1972, and Appendix A). This plot combines the responses of sonic, neutron, and density logs. The trend of data indicates a fluid/matrix combination lighter than water-filled sandstone or limestone. Fracturing may also be present.

POROSITY - LITHOLOGY MODEL

Considering the data trends, a two-mineral model was selected for porosity determination and as an indicator of lithology. The matrix values for this mineral pair are

Mineral #1	Quartz	
	Matrix Density:	2.65 g/cm^3
	Neutron Index:	- 1.5 (limestone) or 0 (sandstone)
Mineral #2	Unknown	
	Matrix Density:	2.52 g/cm^3
	Neutron Index:	0 (limestone) or 1.5 (sandstone)

These values are shown on Figure 4.1 with Mineral #2 noted with a triangular symbol. Figure 4.5 is a chart of the model. The neutron values are converted to sandstone units for a linear response. This model allows the computation of porosity and an apparent matrix density. The dashed lines are the equal-porosity lines between the two minerals. The apparent matrix density is a linear interpolation between 2.65 g/cm^3 for sandstone and 2.52 g/cm^3 for Mineral #2.

APPLICATION OF SONIC DATA

Inspection of the sonic data (Figures 4.2, 4.3, and 4.4) indicates the possibility of fracturing. To check this possibility, an apparent matrix travel time $(t_{ma})a$ was computed by setting the sonic porosity equal to the porosity computed from the two-mineral model. If fracturing is causing the recorded sonic travel time to read too low, the $(t_{ma})a$ will also be lower than would be expected. Figure 4.6 is a frequency crossplot of this $(t_{ma})a$ vs. $(\rho_{ma})a$. This plot also aids in selecting the sonic matrix values for the two minerals. The data trend shows an increasing value of $(t_{ma})a$ with lower $(\rho_{ma})a$ (Lines A and B). Note that both scales are very expanded which results in a wider data spread than on the previous crossplots with normal scaling.

If the recorded sonic log is responding according to the classical description of fracture effects, quantity of fracturing will increase in a direction indicated by Line C.

To check this possibility, a computer program was run to indicate the zones with the greatest likelihood for fractures to occur. (Further discussion of this technique is covered in Task 5 and 6C.) The output of this program is a term "FRAC" which increases in value with increasing indications of fracturing. Figure 4.7 is the same crossplot as Figure 4.6 with the values of FRAC (a range of 1 to 5) printed in place of the frequency of occurrence. For clarity, the FRAC values of 1, 4, and 5 are outlined. The trend indicates less fracturing with higher sonic reading and higher grain density. The greatest amount is associated with the rock of lowest grain density.

DISCUSSION OF INTERPRETATION TECHNIQUE

The two-mineral technique of porosity and lithology interpretation using bulk density and neutron is a commonly used method in cases when the rock characteristics are well known or when one or more of the rock types may be unknown. Advantages of this technique are

1. Simplicity. The technique is easily adaptable to computer processing or manual interpretation via crossplots.
2. Unknown rock types or parameters. In most cases, the matrix values may be determined from crossplots.
3. Porosity determination. The porosity, as determined by this method, is normally very close to true porosity.
4. Lithology determination. The apparent grain density can be used to indicate the rock type or mixtures of two-rock types.

Any petrophysical model has limitations as to the type of formation which may be evaluated.

1. Additional Minerals. Depending on the matrix characteristics and the types of lithology mixtures, it may be possible to build adjoining two-mineral models. If, however, three minerals are mixed together, it is not possible to sort out the lithology without additional data input. Addition of the sonic data may be used to determine lithology of three minerals under the following conditions.
   A. The matrix parameters are different enough to allow resolution of the data.
   B. The logs are responding only to lithology and primary porosity. For example, the sonic log

cannot be influenced by fractures or vugs or mechanical properties of the formation.

2. Utilizing resistivity data. Resistivity data may be used to estimate porosity if additional parameters are known.
   A. Resistivity of formation water at formation temperature (R_w).
   B. a and m for relationship of formation factor ($F = a/\phi^m$). These factors may change with the lithology and pore geometry. Also, resistivities may be influenced by anisotropic characteristics of the rock.

Sample description and cores already identified the type of rock expected. Even then, it was necessary to select matrix parameters from the crossplots. Since granite may have a very wide range of matrix parameters (matrix density 2.45 to 2.94 g/cm^3 and matrix travel time 42.6 to 76.3 $\mu s/ft$), it is not feasible to determine from the logs alone if the data grouped along the quartz matrix line, or the data selected as Mineral #2 is the granite. Notwithstanding the unknowns, the matrix parameters fell in the ranges expected for the type of rock which leads to reasonable porosity values. Verification was made for the detection of fracturing by the classical definition of effects on the sonic log.

The analog playback (Figure 4.16) enclosed is the result of the described two-mineral model interpretation technique.

RAFT RIVER GEOTHERMAL RESERVOIR

The Raft River Geothermal Reservoir is located in south-central Idaho, Cassia County. The upper 1 402m (4 600 ft) is primarily tuffaceous siltstone, conglomerate, and sandstone. Below this sequence, a metamorphic zone of phyllite, schist, and quartzite rests on the quartz monzonite basement rock. The water production from Raft River Reservoir is dependent on highly fractured zones (Stoker and others).

A 530m (1 740-ft) interval was selected for study of lithology definition. Porosity and M-N crossplots are made for two zones from the RRGE #2 well.

1 658 - 1 422 m (5 440 - 4 665 ft): Schist, quartzite, etc. (Figs. 4.8 - 4.11).

1 422 - 1 295 m (4 665 - 4 250 ft): Tuffaceous siltstone, etc. (Figs. 4.12 - 4.15).

The crossplots of the deeper interval fall into three groups.

Group 1: Quartz Monzonite and Quartzite. The porosity data plots primarily between the classical matrix lines of sandstone and limestone. Distinction between the two can be made by two characteristics. The quartz monzonite (1 524m (5 000 ft.) and deeper - see enclosed logs) is predominantly less dense than the quartzite as reflected by the density log. The neutron log, however, shows both types of rocks to have very little porosity or associated water or hydrogen. Another distinctive characteristic is the Gamma Ray. The quartz monzonite is very radioactive as compared to the quartzite. In fact, so radioactive that the gamma-ray detector was saturated or recording limits reached for most of the interval.

Group 2: Mica Schist. The location of mica schist on the three-porosity crossplots is an example of how only two-porosity logs can be misleading in lithology interpretation (1 423 - 1 442 m (4 670 - 4 730 ft) on logs).

Density-Neutron crossplot:

Data plots between limestone and dolomite.

Sonic-Neutron crossplot:

Data plots between sandstone and limestone.

Density-Sonic crossplot:

Data appears more dense than dolomite or with a larger transit time.

The mica schist is more dense than the quartzite or quartz monzonite, but with a higher neutron hydrogen index.

Group 3: The interval 1 734 - 1 756 m (5 690 - 5 760 ft) is shown on the crossplots as having the highest density and the highest neutron hydrogen index. The transit time is around 164 μs/m (50 μs/ft). The lithology of this zone has not been precisely identified, although correlation between wells is fairly straightforward. The porosity data plots in the same area as biotite. However, biotite is 8.7% potassium by weight and should reflect much more radioactivity than the 30 API units on the gamma ray log. Extensive hydrothermal alteration has occurred in the Raft River Reservoir and various transformations may have taken place.

A characteristic of the sonic log was noted on the heading by the Logging Engineer while monitoring the acoustical wave train on an oscilloscope. The compressional wave was greatly reduced and at times almost gone over the deepest section of well. The result of this can be seen as the erratic readings of the sonic as shown in the computer playback of digitized data. A second set of logging tools was tried with the same results. Such tool response would record the transit time of the compressional (P) wave, the shear (S) wave, or a value between the two. Additional data is needed to decisively determine the formation characteristics which would cause this particular tool response.

The zone above 1 422m (4 665 ft) shows a wide range of porosity with most data points around the limestone line or between limestone and sandstone. The M-N crossplot, which eliminates the porosity variable and responds mostly to lithology, shows one dominant trend likely to occur with two minerals and their combinations. With the wide range of parameters possible for tuffaceous material, separation of lithology types will require additional information to identify the trends.

Porosity is computed using a standard three-mineral model, with classical values for sandstone, limestone, and dolomite. Two playbacks are enclosed for comparison to the crossplot data (Figures 4.17 and 4.18).

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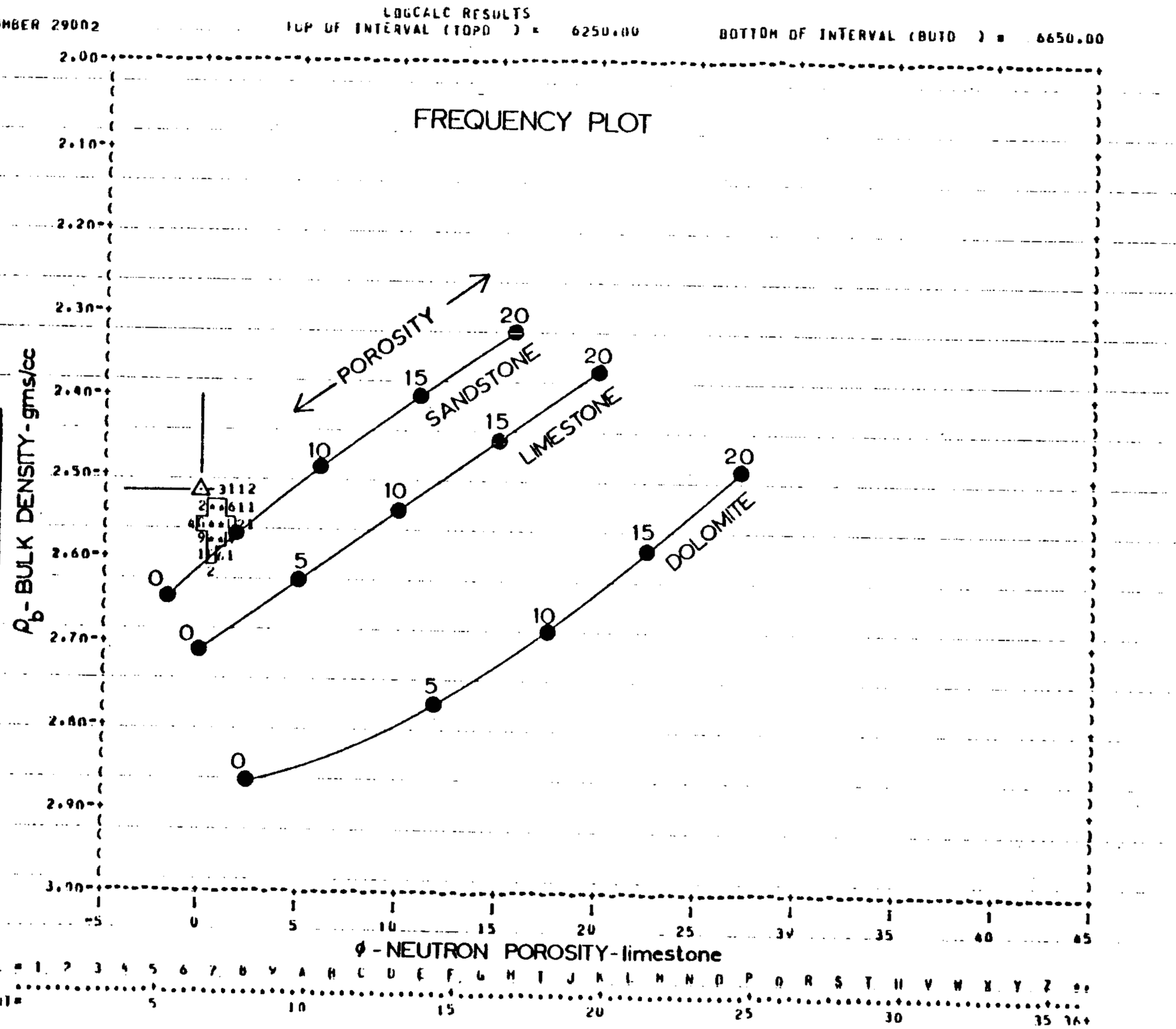
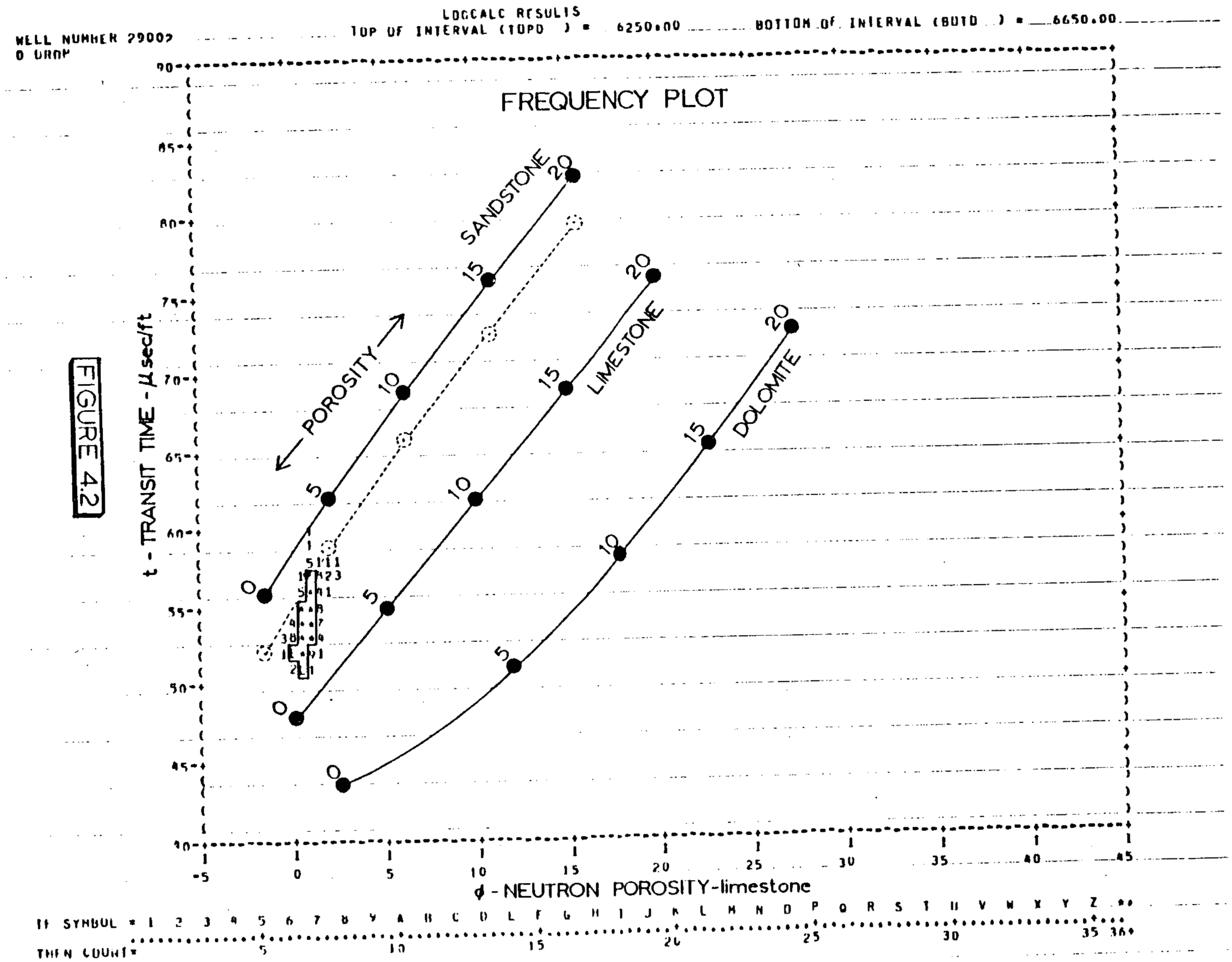


WELL NUMBER 29002
D DROP
LOGCALC RESULTS
TOP OF INTERVAL (TOPD) = 6250.00
BOTTOM OF INTERVAL (BOTD) = 6650.00
FREQUENCY PLOT
POROSITY
SANDSTONE
LIMESTONE
DOLOMITE
ρ_b - BULK DENSITY - gms/cc
ϕ - NEUTRON POROSITY - limestone
2.00
2.10
2.20
2.30
2.40
2.50
2.60
2.70
2.80
2.90
3.00
-5
0
5
10
15
20
25
30
35
40
45
IF SYMBOL = 1 2 3 4 5 6 7 8 9 A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
THEN COUNT= 5 10 15 20 25 30 35 36+

FIGURE 4.1


LOGCALC RESULTS
WELL NUMBER 29002
D DROP
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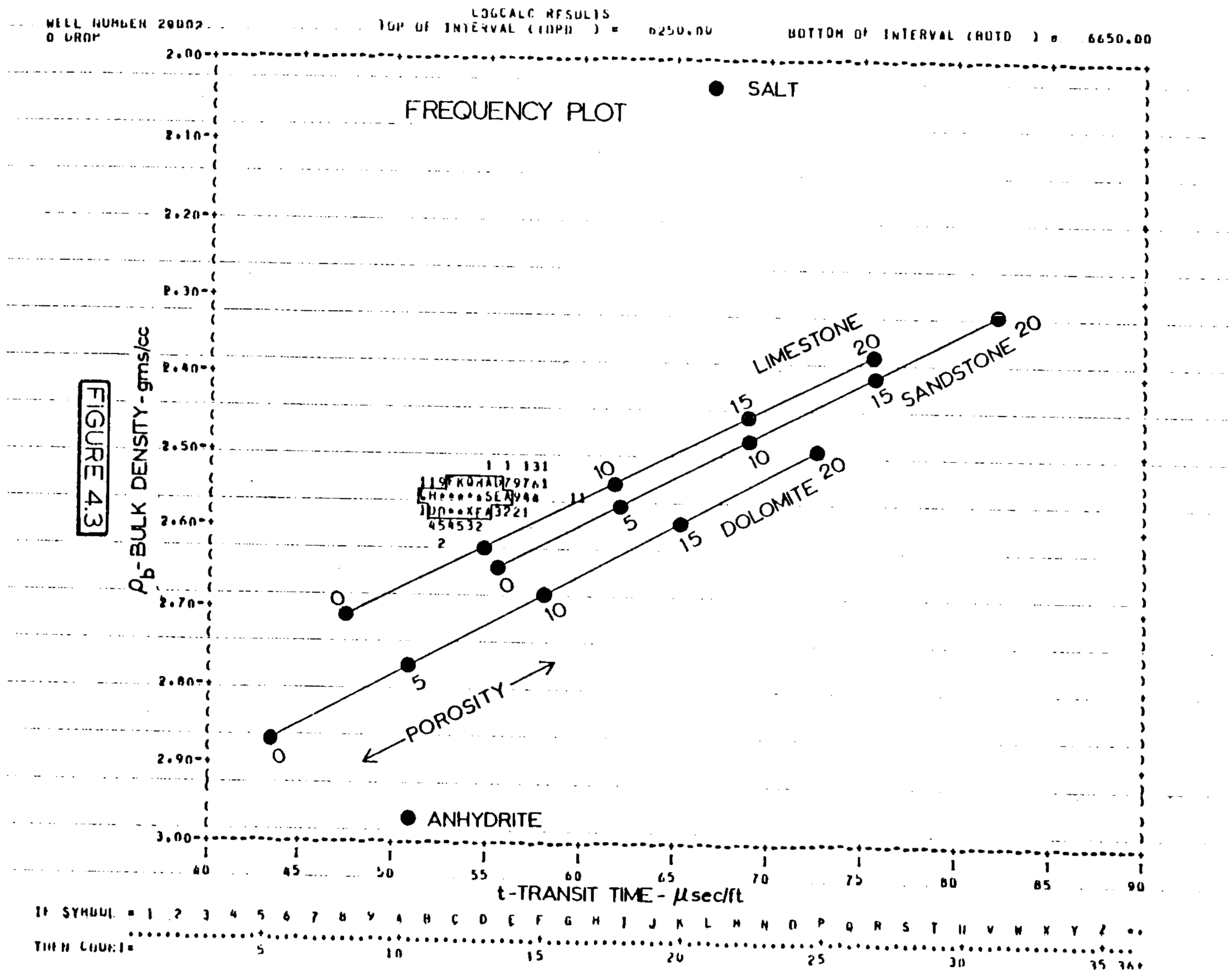
BOTTOM OF INTERVAL (BOTD) = 6650.00
FREQUENCY PLOT
SANDSTONE
LIMESTONE
DOLOMITE
POROSITY
t - TRANSIT TIME - μsec/ft
φ - NEUTRON POROSITY-limestone
IF SYMBOL = 1 2 3 4 5 6 7 8 9 A B C D E F G H I J K L M N O P Q R S T U V W X Y Z **
THEN COUNT=

FIGURE 4.2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BOTTOM OF INTERVAL (BOTD) = 6650.00
FREQUENCY PLOT
SALT
LIMESTONE
SANDSTONE
DOLOMITE
POROSITY
ANHYDRITE
ρ_b - BULK DENSITY - gms/cc
t-TRANSIT TIME - μsec/ft
2.00
2.10
2.20
2.30
2.40
2.50
2.60
2.70
2.80
2.90
3.00
40
45
50
55
60
65
70
75
80
85
90

FIGURE 4.3

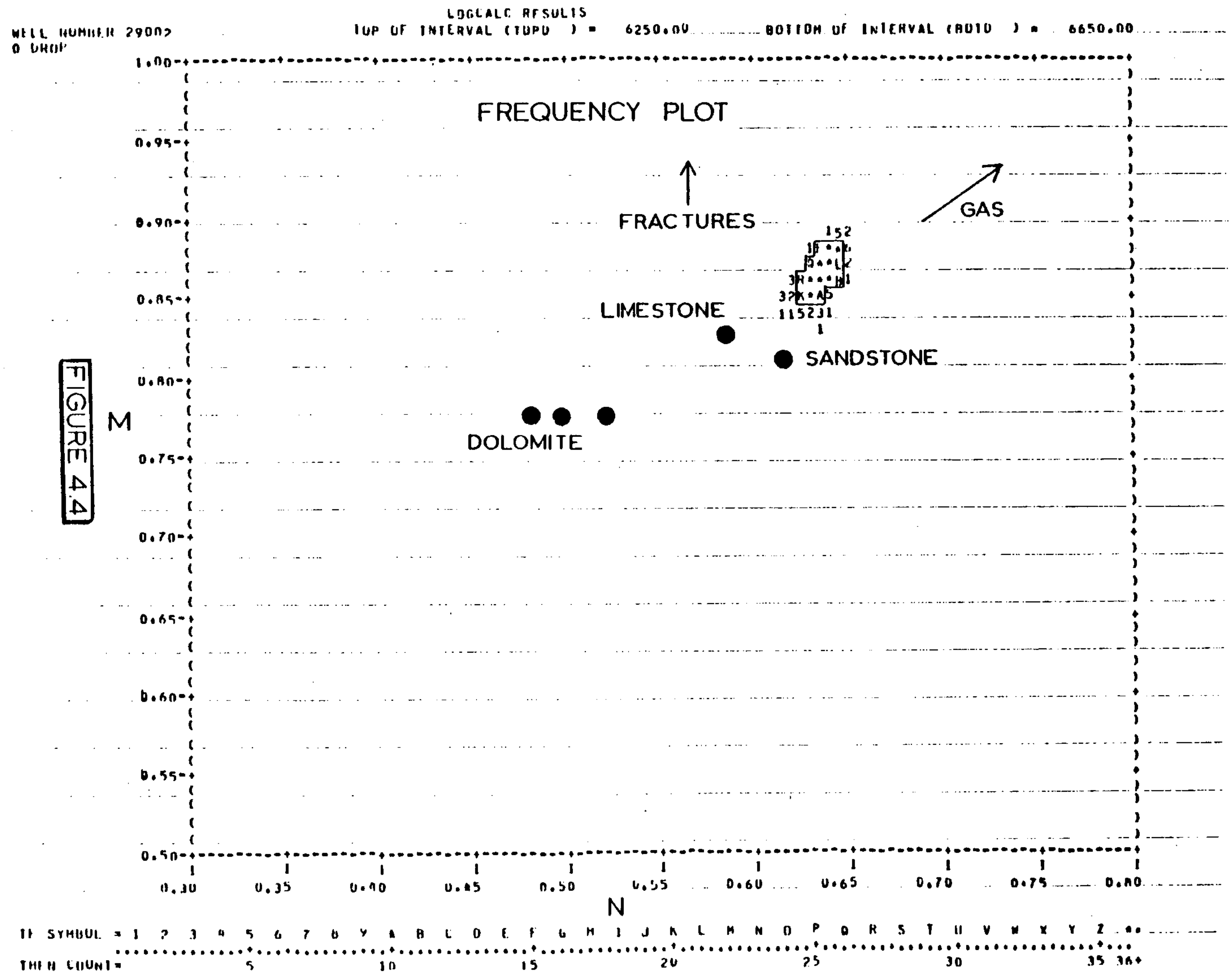
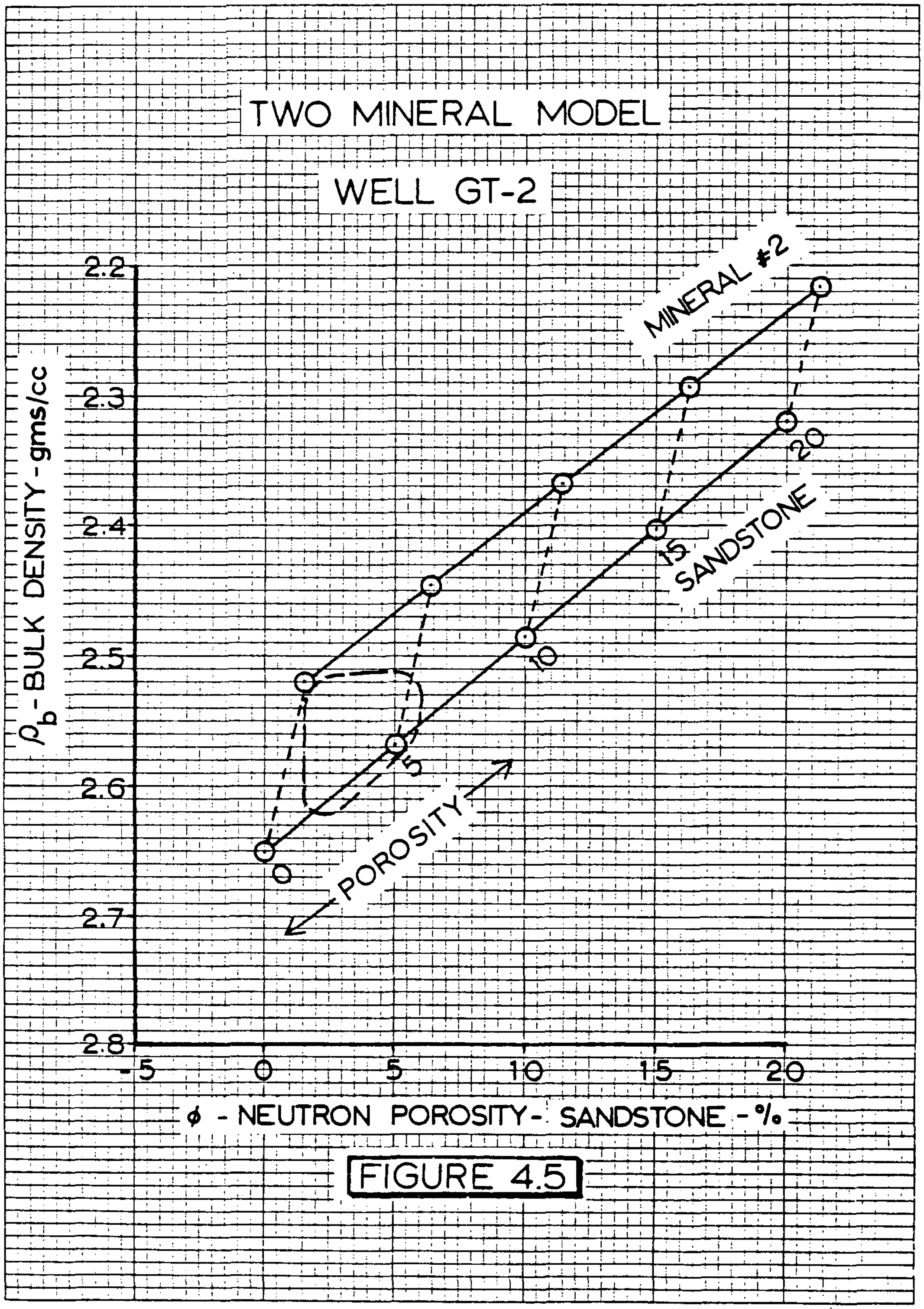
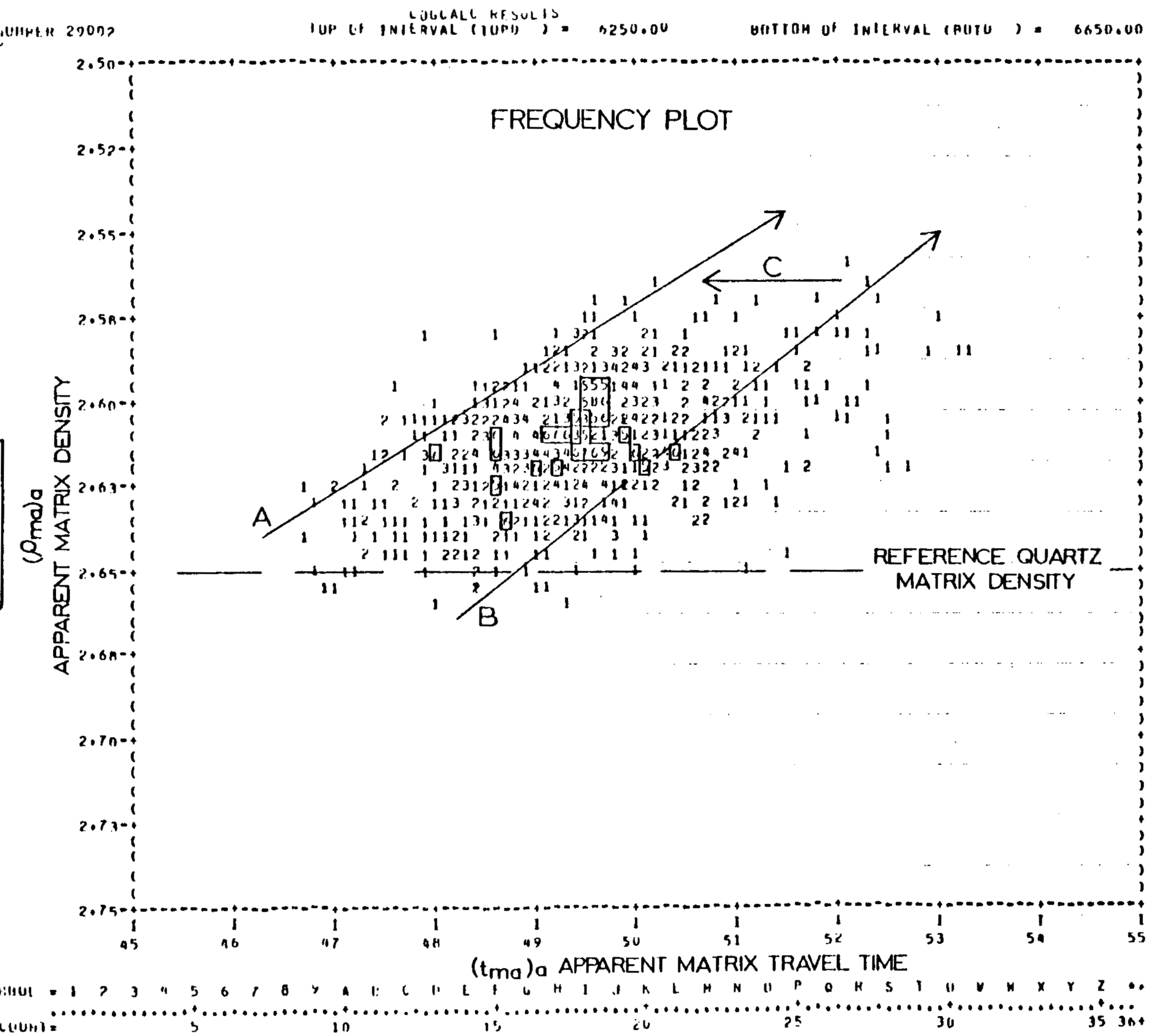

LOGCALC RESULTS
WELL NUMBER 29002
O DROP
TOP OF INTERVAL (TOPD) = 6250.00
BOTTOM OF INTERVAL (BOTD) = 6650.00
FREQUENCY PLOT
FRACTURES
GAS
LIMESTONE
SANDSTONE
DOLOMITE
M
N
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.80
IF SYMBOL = 1 2 3 4 5 6 7 8 9 A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
THEN COUNT= 5 10 15 20 25 30 35 36+

FIGURE 4.4



TWO MINERAL MODEL
WELL GT-2
MINERAL #2
SANDSTONE
POROSITY
0
5
10
15
20
2.2
2.3
2.4
2.5
2.6
2.7
2.8
-5
ρ_b - BULK DENSITY - gms/cc
ϕ - NEUTRON POROSITY - SANDSTONE - %

FIGURE 4.5



LOGCALC RESULTS
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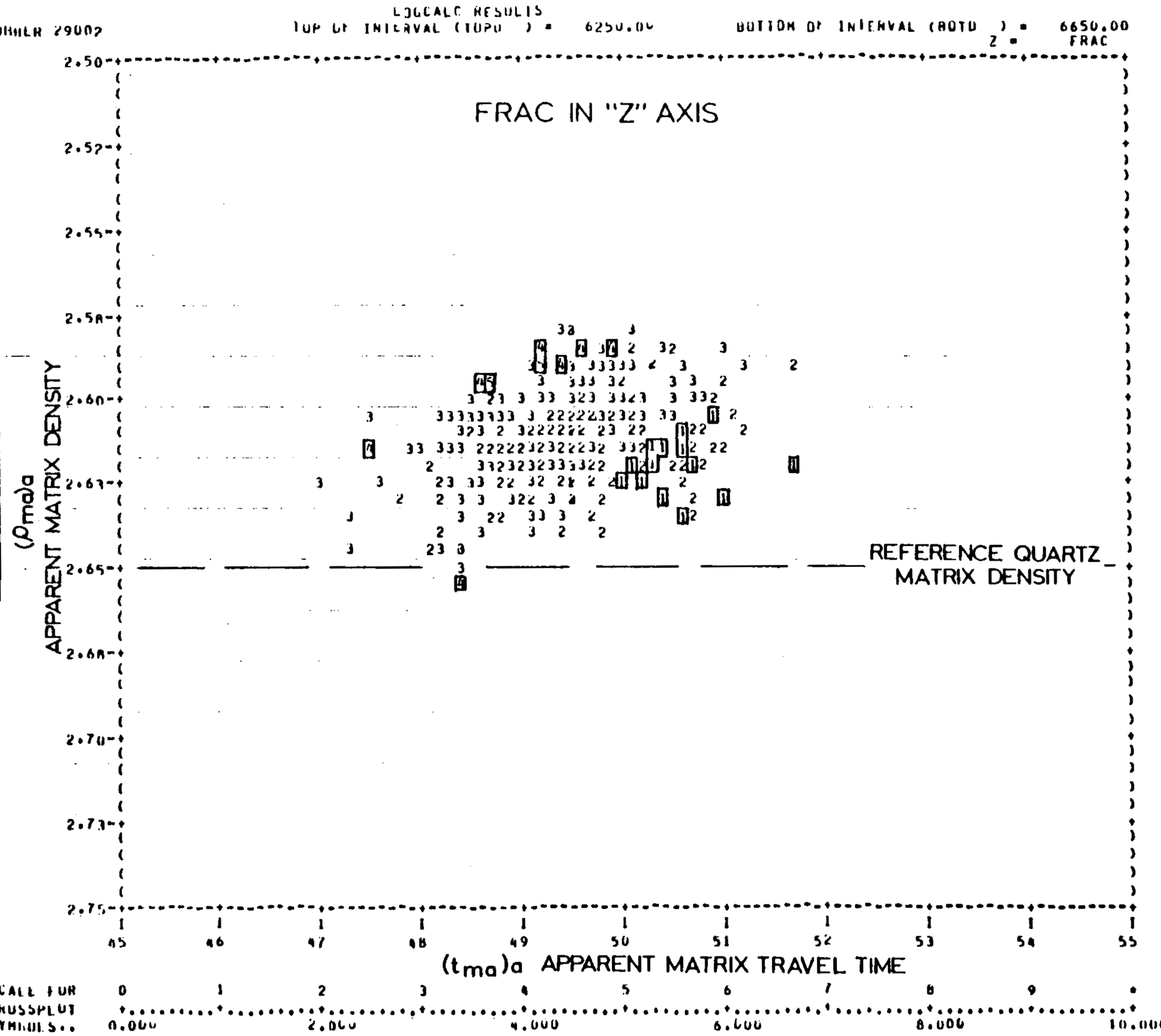
BOTTOM OF INTERVAL (BOTD) = 6650.00
FREQUENCY PLOT
A
B
C
REFERENCE QUARTZ MATRIX DENSITY
$(\rho_{ma})_a$ APPARENT MATRIX DENSITY
$(t_{ma})_a$ APPARENT MATRIX TRAVEL TIME

FIGURE 4.6


LOGCALC RESULTS
WELL NUMBER 29002
1 GROUP
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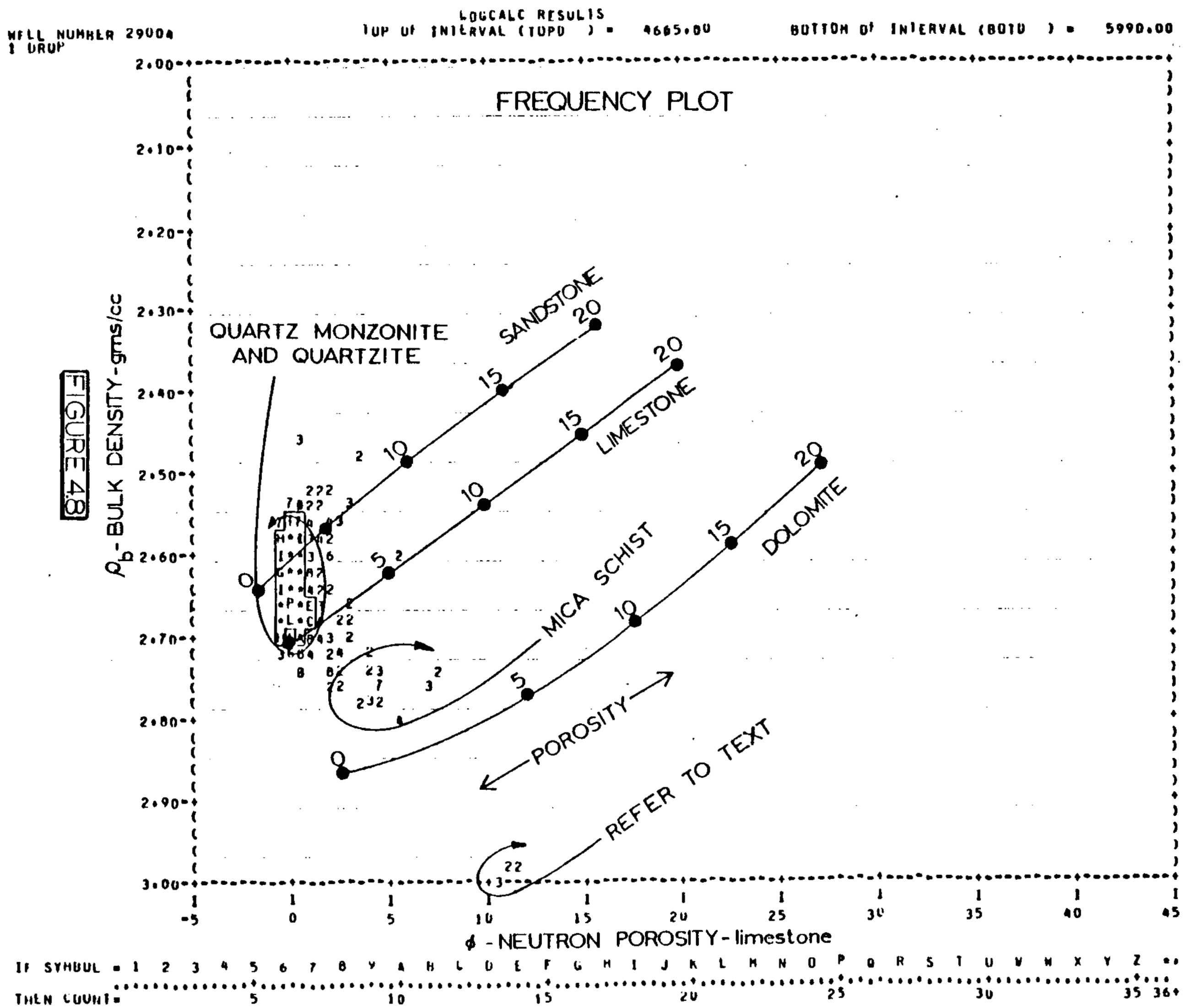
BOTTOM OF INTERVAL (BOTD) = 6650.00
Z = FRAC
FRAC IN "Z" AXIS
(ρ_{ma})a APPARENT MATRIX DENSITY
REFERENCE QUARTZ MATRIX DENSITY
(t_{ma})a APPARENT MATRIX TRAVEL TIME
SCALE FOR CROSSPLOT SYMBOLS..

FIGURE 4.7


LOGCALC RESULTS
WELL NUMBER 29004
1 DROP
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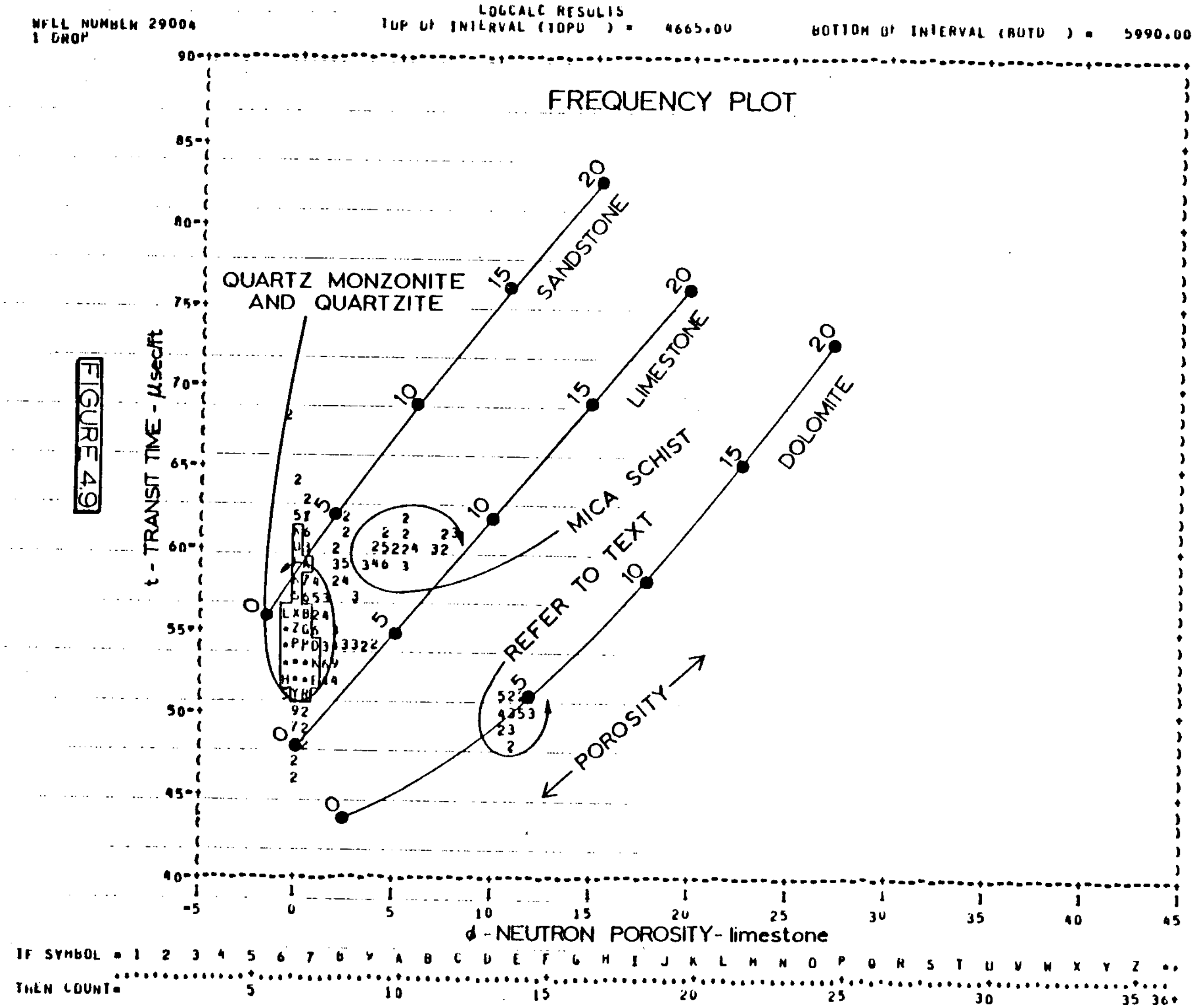
BOTTOM OF INTERVAL (BOTD) = 5990.00
FREQUENCY PLOT
QUARTZ MONZONITE AND QUARTZITE
SANDSTONE
LIMESTONE
MICA SCHIST
DOLOMITE
POROSITY
REFER TO TEXT
ρ_b - BULK DENSITY - gms/cc
ϕ - NEUTRON POROSITY - limestone
2.00
2.10
2.20
2.30
2.40
2.50
2.60
2.70
2.80
2.90
3.00
-5
0
5
10
15
20
25
30
35
40
45
IF SYMBOL = 1 2 3 4 5 6 7 8 9 A B C D E F G H I J K L M N O P Q R S T U V W X Y Z *
THEN COUNT= 5 10 15 20 25 30 35 36+

FIGURE 4.8



LOGCALC RESULTS
WELL NUMBER 29004
1 DROP
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BOTTOM OF INTERVAL (BOTD) = 5990.00
FREQUENCY PLOT
QUARTZ MONZONITE AND QUARTZITE
SANDSTONE
LIMESTONE
DOLOMITE
MICA SCHIST
REFER TO TEXT
POROSITY
t - TRANSIT TIME - μsec/ft
ϕ - NEUTRON POROSITY - limestone
IF SYMBOL = 1 2 3 4 5 6 7 8 9 A B C D E F G H I J K L M N O P Q R S T U V W X Y Z *.
THEN COUNT= 5 10 15 20 25 30 35 36+

FIGURE 4.9

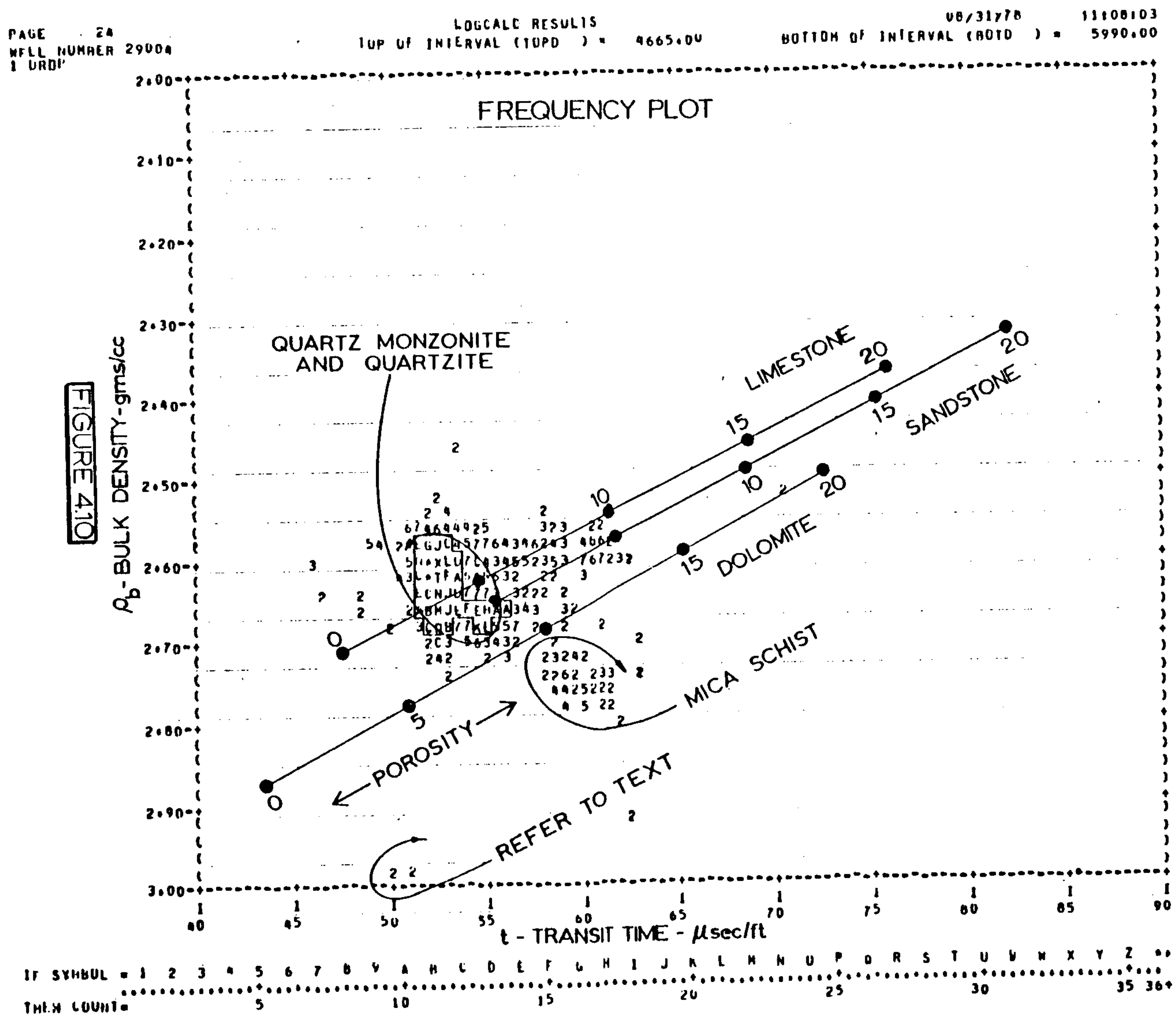
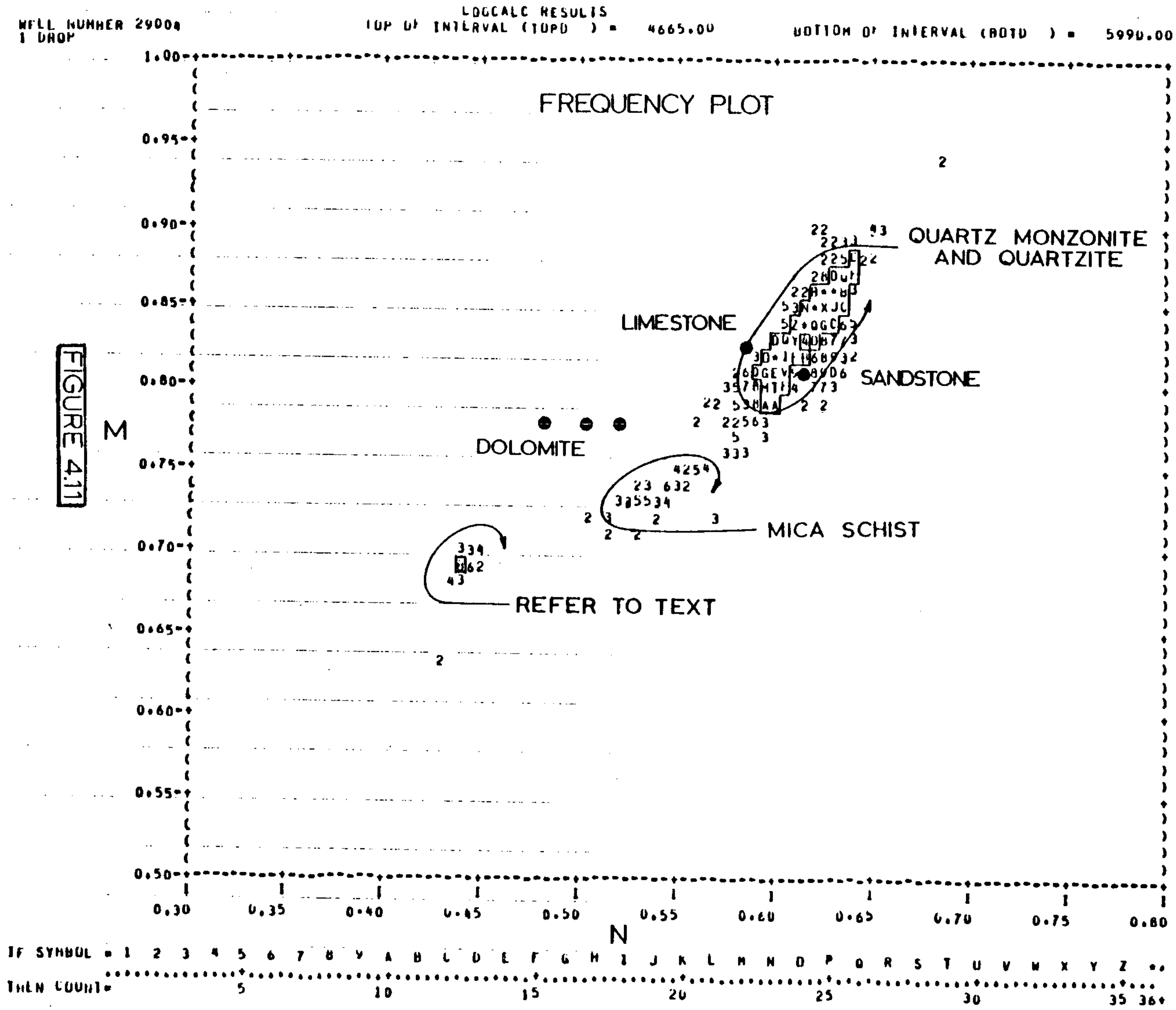

PAGE 24
WELL NUMBER 2900A
LOGCALC RESULTS
TOP OF INTERVAL (TOPD) = 4665.00
08/31/78 11:08:03
BOTTOM OF INTERVAL (BOTD) = 5990.00
FREQUENCY PLOT
QUARTZ MONZONITE AND QUARTZITE
LIMESTONE
SANDSTONE
DOLOMITE
MICA SCHIST
POROSITY
REFER TO TEXT
ρb - BULK DENSITY-gms/cc
t - TRANSIT TIME - μsec/ft
IF SYMBOL = 1 2 3 4 5 6 7 8 9 A B C D E F G H I J K L M N O P Q R S T U V W X Y Z **
THEN COUNT=

FIGURE 4.10


LOGCALC RESULTS
WELL NUMBER 2900
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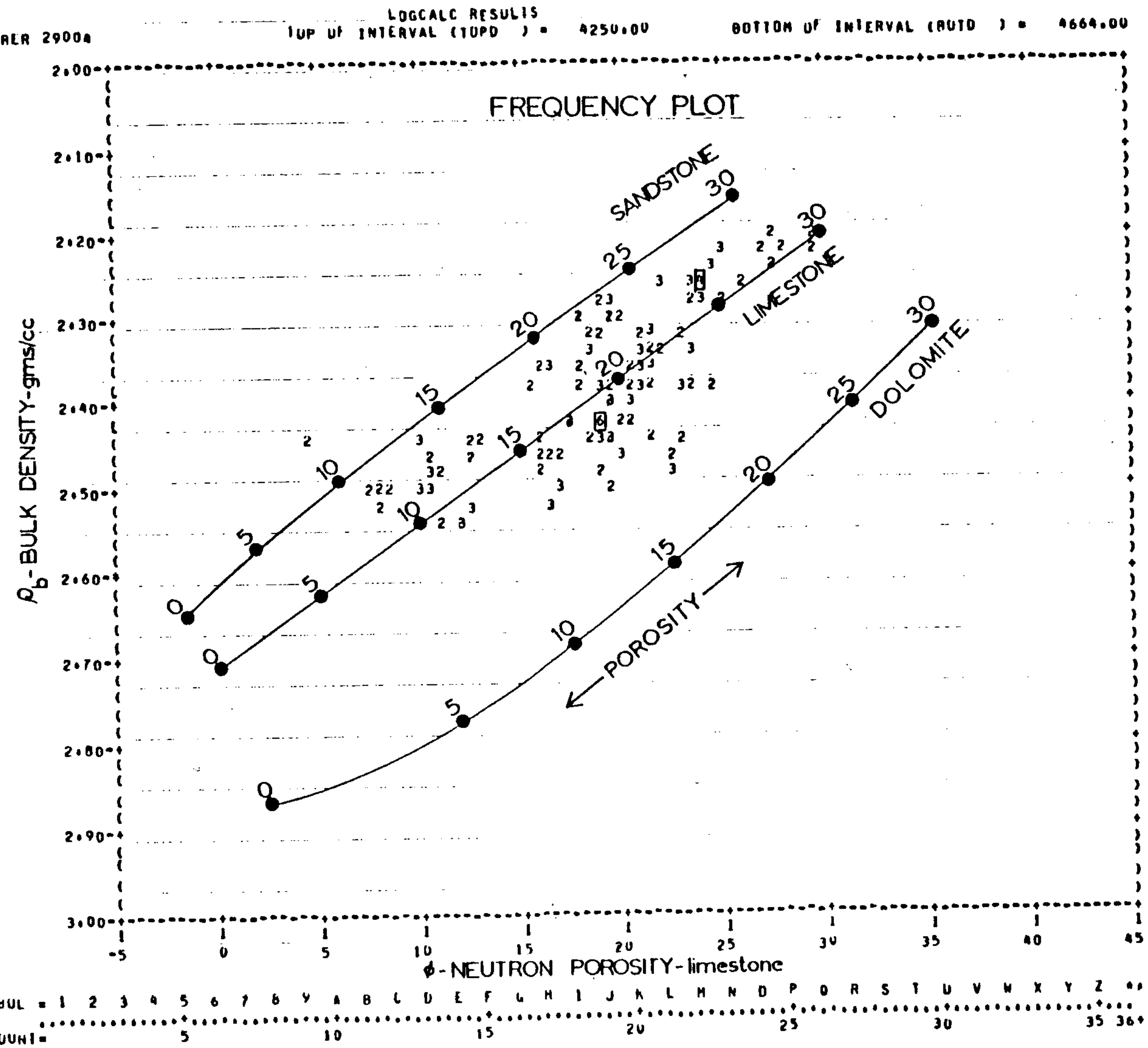
BOTTOM OF INTERVAL (BOTD) = 5990.00
FREQUENCY PLOT
QUARTZ MONZONITE AND QUARTZITE
LIMESTONE
SANDSTONE
DOLOMITE
MICA SCHIST
REFER TO TEXT
M
N
IF SYMBOL = 1 2 3 4 5 6 7 8 9 A B C D E F G H I J K L M N O P Q R S T U V W X Y Z *
THEN COUNT= 5 10 15 20 25 30 35 36+

FIGURE 4.11


LOGCALC RESULTS
WELL NUMBER 29004
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BOTTOM OF INTERVAL (BOTD) = 4664.00
FREQUENCY PLOT
SANDSTONE
LIMESTONE
DOLOMITE
POROSITY
ρ_b-BULK DENSITY-gms/cc
ϕ-NEUTRON POROSITY-limestone
IF SYMBOL = 1 2 3 4 5 6 7 8 9 A B C D E F G H I J K L M N O P Q R S T U V W X Y Z **
THEN COUNT= 5 10 15 20 25 30 35 36+

FIGURE 4.12

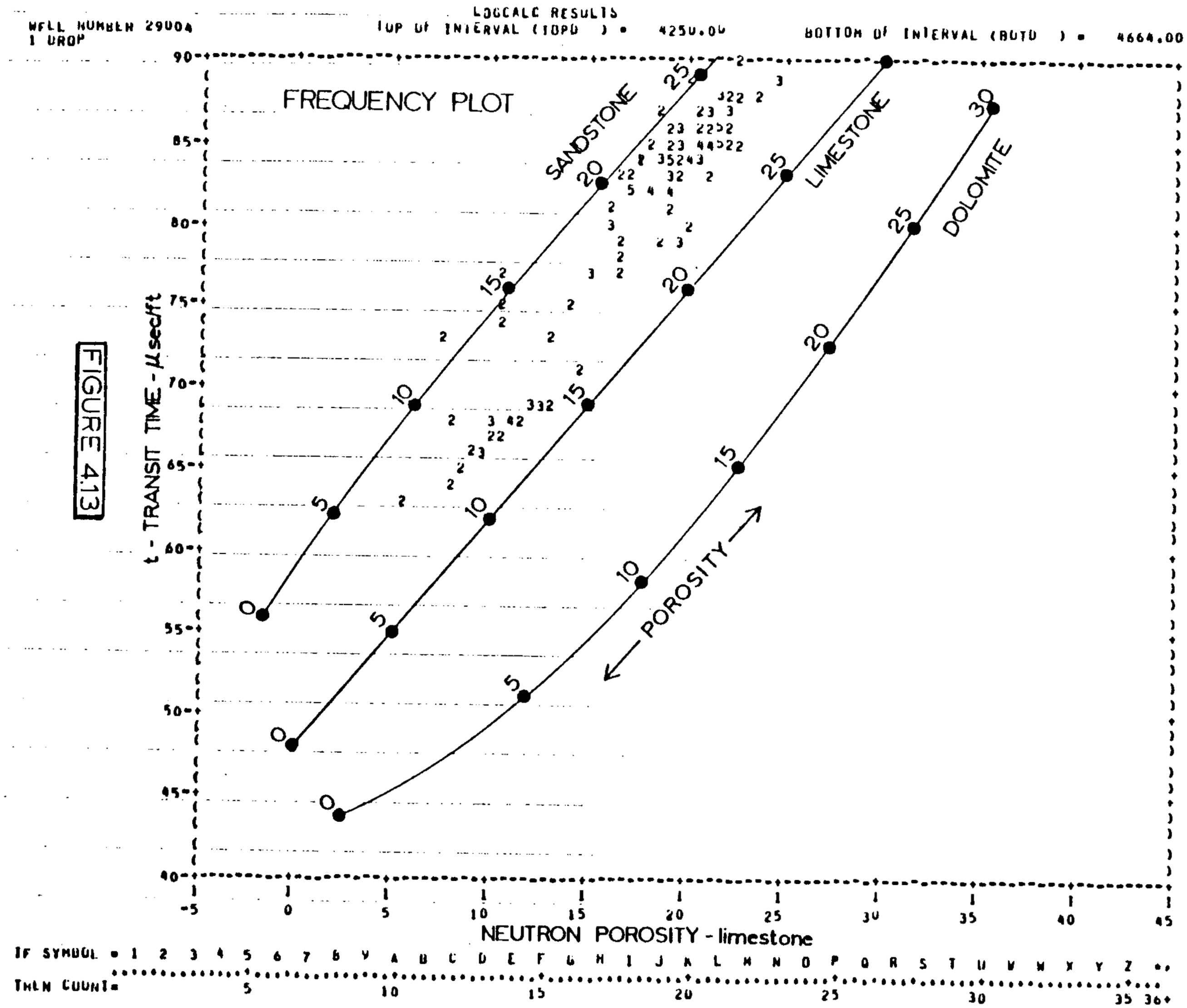
WELL NUMBER 29004
1 DROP
LOGCALC RESULTS
TOP OF INTERVAL (TOPD) = 4250.00
BOTTOM OF INTERVAL (BOTD) = 4664.00
FREQUENCY PLOT
SANDSTONE
LIMESTONE
DOLOMITE
POROSITY
t - TRANSIT TIME - μsec/ft
NEUTRON POROSITY - limestone
IF SYMBOL = 1 2 3 4 5 6 7 8 9 A B C D E F G H I J K L M N O P Q R S T U V W X Y Z *
THEN COUNT= 5 10 15 20 25 30 35 36+

FIGURE 4.13

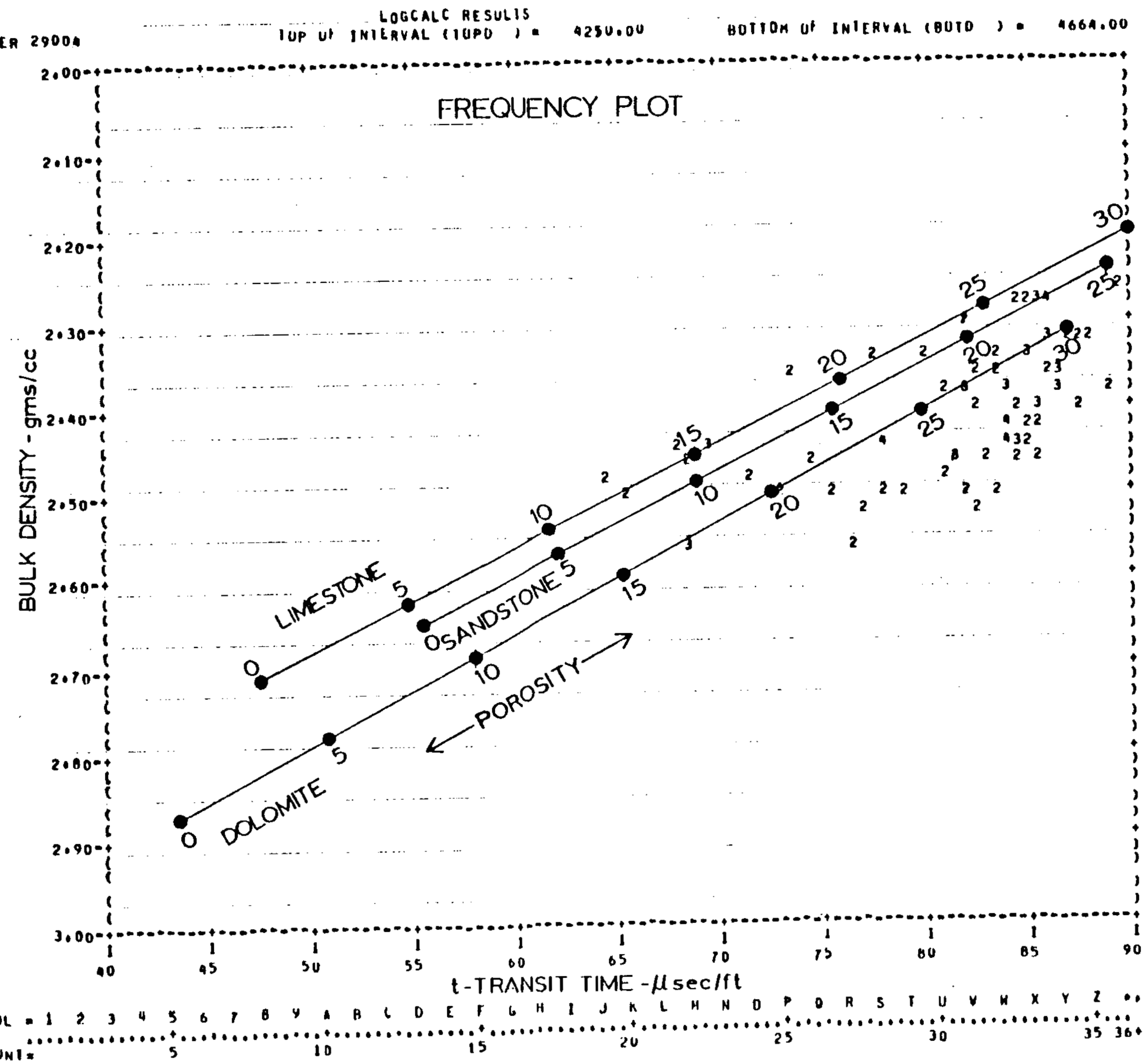
LOGCALC RESULTS
WELL NUMBER 29004
1 DROP
TOP OF INTERVAL (TOPD) = 4250.00
BOTTOM OF INTERVAL (BOTD) = 4664.00
FREQUENCY PLOT
BULK DENSITY - gms/cc
LIMESTONE
SANDSTONE
DOLOMITE
POROSITY
t-TRANSIT TIME - μsec/ft
IF SYMBOL = 1 2 3 4 5 6 7 8 9 A B C D E F G H I J K L M N O P Q R S T U V W X Y Z *
THEN COUNT=

FIGURE 4.14

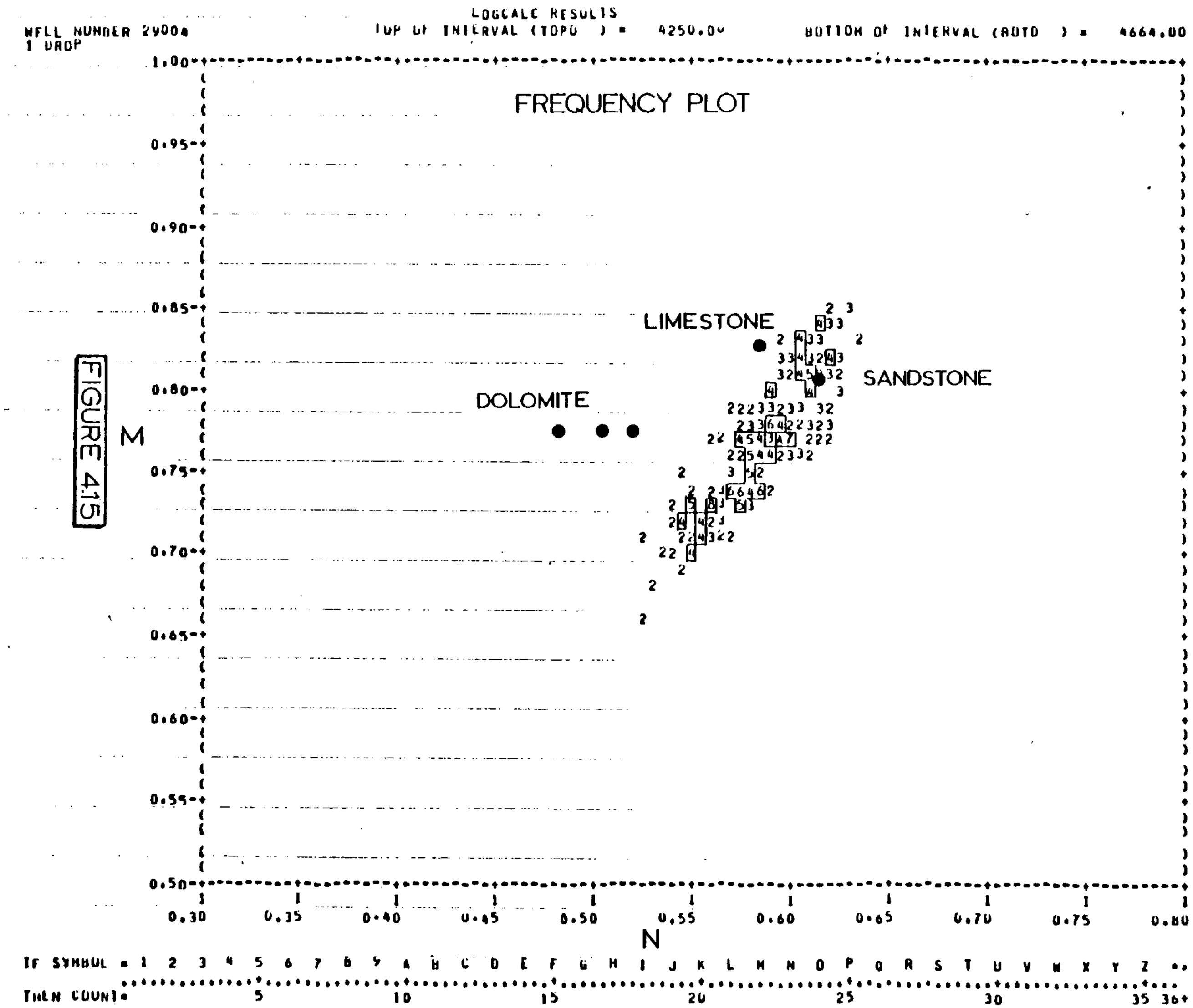
LOGCALC RESULTS
WELL NUMBER 29004
1 DROP
TOP OF INTERVAL (TOPO) = 4250.00
BOTTOM OF INTERVAL (ROTD) = 4664.00
FREQUENCY PLOT
LIMESTONE
DOLOMITE
SANDSTONE
M
N
IF SYMBOL = 1 2 3 4 5 6 7 8 9 A B C D E F G H I J K L M N O P Q R S T U V W X Y Z *
THEN COUNT=

FIGURE 4.15

NOTES

TASK-5: REFINEMENT OF EXISTING INTERPRETATION TECHNIQUES AND DEVELOPMENT OF NEW ONES

Subtask A: Development of Petrophysical Models

For quantitative interpretation of well log data, a "petrophysical model" of the formation must be available. Essentially such a model is an idealized representation of the nature of the formation as it pertains to its fluid storage and flow capacities, as well as some thermal and mechanical properties. There are three basic components in such a model: matrix, pore space, and fluids. These components are described below. Based on such a model, one can derive log response equations. These equations can then be used to calculate petrophysical parameters from observed log responses.

Matrix

The matrix is the solid part of the formation. It includes primary matrix minerals, cementing materials, and mineral accumulations that took place after lithification. Any property of the matrix is primarily a function of its mineral composition. The properties of the matrix have a strong influence on the log response of a formation, for matrix volume is usually much larger than the fluid volume in the formation.

Most matrix materials encountered in logging are electrically nonconductive. One notable exception is shale; the wet clay minerals in shale can impart considerable electrical conductivity to the matrix. Another exception is graphite and a group of metallic minerals such as pyrite which are conductive. The conductivity of wet clays is due to ionic double-layer conductivity; that of metallic minerals is due to electronic conduction. Conductivity of shales can vary considerably depending on the composition of the shale. The conductivity of pure metallic minerals is less variable. However, the relative arrangement and amounts of the conductive and nonconductive components of a formation matrix determine the overall conductivity of the matrix. Hence, a petrophysical model incorporating the structural arrangement of various matrix components, pores, and fluids is necessary. There are other factors influencing the contribution of the conductive components of a matrix to the overall matrix conductivity. In the case of shale, the salinity of the formation water is such a factor--the higher the formation water conductivity, the lower is the relative effect of clay. Clavier and others (1976) found that for the range of frequencies used in resistivity logging, the relative contribution of pyrite to the overall matrix conductivity is a function of the frequency of the measuring current.

Other physical properties of the matrix such as the bulk density, sonic velocity, hydrogen index, neutron capture cross section, electromagnetic propagation time, etc., also depend on the property of the matrix components. However, matrix properties such as bulk density, neutron capture cross section, and hydrogen index are independent of the relative arrangement of the matrix components, while sonic velocity and electromagnetic propagation time may not be so.

The response equations of many logs include parameters quantifying matrix properties. The most important of such parameters are the sonic travel time (Δt_{ma}), bulk density (ρ_{ma}), and the neutron porosity in limestone units ($\phi_{n,ma}$) being required for quantitative analysis of sonic, density, and neutron logs, respectively. The general form of the response equations for most logs can be written as

$$A = A_f(\phi) + A_{ma}(1 - \phi), \qquad (1)$$

where A denotes a physical property (such as sonic travel time, bulk density, neutron porosity, neutron capture cross section, electromagnetic propagation time), and Φ is porosity. Subscripts "ma" and "f" refer to matrix and fluids, respectively. If the matrix is composed of n components, then

$$A_{ma} = \sum_{i=1}^{n} A_{ma,i} X_i \quad , \qquad (2)$$

where $A_{ma,i}$ denotes the physical property and X_i the matrix volume fraction of the ith component in the matrix.

In Eq. (1), A is read from a log, and A_f and A_{ma} values are usually obtained from tables based on laboratory data. Then Φ can be calculated. However, if the matrix has more than one component, X_i's need to be known before Eq. (1) can be used to calculate porosity. If n logs are available, n equations of the form of Eq. (1) can be set up and solved for n unknowns such as Φ and $X_1, X_2, \ldots X_{n-1}$. Then from material balance

$$X_n = 1 - X_1 - X_2 - \ldots\ldots X_{n-1}. \qquad (3)$$

Thus matrix properties of various minerals and rocks are extremely important in log analysis. Such data are available from the logging manuals only for a limited number of lithologies. The data are scanty or nonexistent for most of the lithologies encountered in geothermal reservoirs.

There are essentially three ways of obtaining data on matrix properties: laboratory measurements, derivation from log responses in "tight" zones, and calculation from multilog suites. Laboratory-derived data reported in the literature are usually obtained under ambient condition, while the reservoir condition is different--the pressure and temperature are higher. Some matrix properties such as the sonic velocities (shear or compressional) are functions of temperature (Somerton and others, 1974; Timur, 1976). This fact should be considered in interpreting geothermal well logs. Matrix properties can sometimes be derived from logs through "tight" zones. If a well section is known to be nonporous ("tight"), its log response is the same as the matrix response for the lithology around the well bore. When a multilog suite is available, one can set up a number of linear response equations, as explained earlier, and solve these equations. The unknowns in these equations are usually the porosity and the relative volume of the various matrix components. However, if either porosity or the relative volumes of some components are known, then some matrix properties can be calculated. For example, given the density and neutron logs through a formation with a two-component matrix of known composition, one can calculate the porosity of the formation and $\phi_{n,ma}$ of one of the components, if $\phi_{n,ma}$ of the other component and the bulk densities of both components are known. Such estimates can often be made with the help of logging charts or crossplots. For some logs it is difficult to use the concept of "matrix property" quantitatively. For example, the gamma-ray log response of a formation is a function of the amount (usually minute) of radioactive minerals in the formation. It is difficult to assign a "typical" gamma-ray response to any particular lithologic component. Nevertheless, the gamma-ray log is used to estimate the bulk volume shale fraction in a formation by assuming that the gamma-ray responses of adjacent shale and "clean" sand beds are the same as the gamma-ray responses of the "shale" and "sand" fractions, respectively, in the matrix of the formation in question. The petrophysical model usually employed for the calculation of the bulk volume shale fraction (V_{sh}) is

$$V_{sh} = \frac{GR - GR_{sd}}{GR_{sh} - GR_{sd}} \quad , \qquad (4)$$

where GR, GR_{sd}, and GR_{sh} are the gamma-ray intensities of the zone under study, of sand, and of shale, respectively. Equation (4) tends to overestimate V_{sh}. A more accurate version of the model gives

$$V_{sh} = \frac{GR \cdot \rho - GR_{sd} \cdot \rho_{sd}}{GR_{sh} \cdot \rho_{sh} - GR_{sd} \cdot \rho_{sd}} , \qquad (5)$$

where ρ is the bulk density (obtained from a density log) of the zone under study, and ρ_{sd} and ρ_{sh} are the bulk densities of the zones at which GR_{sd} and GR_{sh} are read. Usually, this V_{sh} is also too high (Dresser Atlas, 1977).

The SP log measures the spontaneous potential, which consists of electrochemical and streaming potential components. Streaming potential is independent of the matrix properties but is an indirect function of pore geometry. Electrochemical potential is a function of the relative content of some matrix components, such as shale and the chemical characteristics of the formation and borehole fluids.

Interpretation of temperature logs may require knowledge of the thermal properties (thermal conductivity and specific heat) of the matrix. If the matrix of a known composition and the specific heats of each component are known then the overall specific heat (C) of the matrix can be calculated as

$$C = \sum_{i=1}^{n} C_i X_i , \qquad (6)$$

when C_i and X_i are the specific heat and the mass fraction (in matrix), respectively, of the ith component, and n is the number of components. However, no such simple relation is available for estimating the thermal conductivity of a complex lithology.

Pore Space

The pore space in a petrophysical model implies space within the rock that is not occupied by matrix material. Two important characteristics of pore spaces that need to be accounted for in petrophysical models are the pore geometry (or pore structure) and the amount of pore space relative to the matrix volume, usually expressed as fraction of the bulk volume of the rock (porosity). Porosity may be subdivided into different types; intergranular, fracture, vuggy, vesicular, and oolitic porosities.

Intergranular porosity means spaces left between the grains of a matrix, and are generally interconnected and fairly regular. Porosities of this type are present in most sedimentary formations. Fracture porosity may be naturally caused by geologic events after deposition or is sometimes artifically generated by hydraulic or explosive fracturing to enhance formation permeability. Fracture porosity can be present in all types of formations; however, it is dominant in igneous and metamorphic rocks. Vuggy porosity is caused by solution of the matrix material, and the vugs may or may not be interconnected. This type of porosity is of common occurrence in carbonate formations. Vesicular porosity is sometimes encountered in volcanic rocks. This porosity is caused when the gas released from a cooling lava is trapped as a series of gas bubbles throughout the matrix. It should be pointed out that for vuggy and vesicular porosities there is no limit to the amount of pore space per volume of matrix, whereas, for intergranular porosities the pore space will not exceed about 44 percent of the total bulk volume. An extreme case of vesicular porosity is seen in pumice, which is so porous that it floats on water. Oolitic porosity is encountered in some formations deposited in marine environments. Oolitic pores can be divided into micropores, which include the spaces within the oolites and are very small pores; and the pore space between the oolites is referred to as interoolitic pores. Micropores may occur in nonoolitic carbonates and in the cementing material of clastic sediments (Kieke and Hartmann, 1973).

Fluids

The fluid present in the pore spaces of a geothermal reservoir is either steam or water. Steam has practically infinite resistivity compared to water. The resistivity of formation water depends on the salinity and temperature of the water.

Petrophysical Models for Geothermal Reservoirs

Because of the extremely diverse lithologies and pore structures encountered in geothermal reservoirs, it is impossible to have a unique petrophysical model for all geothermal systems. We discuss briefly below some of the most applicable petrophysical models for geothermal log analysis.

1) Intergranular porosity, sedimentary clastic rock without any shale--For resistivity response, the Archie's formula is adequate (Schlumberger, 1972). For porosity logs, standard response equations are applicable. This is known as a "clean sand" model.

2) Intergranular porosity, shaly clastic rocks--Since the presence of shale affects the responses of many well logs, the interpretation of shaly formations is more involved than "clean" formations. Shaliness affects log responses depending on the proportion of shale and its physical properties and the distribution of shale in the formation. The three shale models generally accepted are the following. Laminar shale: Shale

exists in the form of laminae between which are layers of sand. Structural Shale: It exists as grains or nodules in the formation matrix. Dispersed clay: In this case clay is dispersed throughout, partially filling the interstices. It should be pointed out that the three forms of shale may be present simultaneously in the same formation. Schlumberger (1974) provides considerable details of typical shaly formation log analysis.

3) Carbonates with intergranular porosity--This model is similar to the previous ones, except that the presence of shale is usually not a problem, the cementation factor can be generally considered to be 2.0, and the degree of compaction in carbonates is quite high and fairly uniform.

4) Nonconductive matrix with fracture porosity, for example, fractured igneous and metamorphic rocks--The detection and evaluation of fractures is important in geothermal log analysis. The methods available, however, are limited to gross sections where a statistically significant number of zones are available. Analyses of different cases have shown that the cementation exponent ranges from 1.1 to 1.3 for fractured systems. It has also been found that unless the environment is highly fractured the sonic velocity will be unaffected by the presence of fractures. Aguilera (1977) has discussed log analysis in naturally fractured reservoirs. In a later section in this report we have discussed the various techniques for locating fractures from well logs. For igneous rocks, the influence of bound water in minerals must be accounted for in log analysis (Nelson and Glen, 1975). For igneous and metamorphic geothermal reservoirs, the effect of hydrothermal alteration in log response must be considered.

5) Matrix with a conductive metallic mineral, such as pyrite--Both the amount and structural arrangement of the conductive mineral in the rock will affect the log responses. The effect of pyrite on log response has been discussed by Clavier and others (1976); the results are summarized in this report under Task 1 in the section on Laboratory Investigations.

6) Metamorphic Rocks--For lightly metamorphosed rocks, models should be same as for their sedimentary counterparts, unless there is significant development of secondary minerals; for example, refer to the work of Ritch (1975) discussed under Task 1.

7) Volcanic ash and tuff--Refer to the discussion on the work of Khatchikian and Lesta (1973) and Sacco (1978) under Task 1.

8) Vuggy and oolite carbonates--Models for vuggy carbonates are the same for other carbonates except for the consideration of secondary porosity. No model has been specifically developed for oolite carbonates. Vugs will not alter the sonic log response.

9) Vesicular volcanic rocks--For interconnected vesicular system, probably Archie's formula will hold. It is not known to what extent the sonic log response will be affected by vesicular porosity. The other aspects of vesicular rock will be similar to that for other igneous rocks.

At this time we are still developing quantitative models. For example, under Task 4, preliminary quantitative models for a mainly volcanic and sedimentary rock sequence (Raft River) and for a granite basement rock (Fenton Hill) sequence are given as examples.

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Subtask B: Matrix Response

The matrix and response values are classified and listed in four tables.

Table 5.b.1: Hierarchical Relationship of Minerals

Table 5.b.2: Hierarchical Relationship of Rocks

Table 5.b.3: Matrix Values for Minerals

Table 5.b.4: Matrix Values for Rocks

Table 5.b.1 and Table 5.b.2 classify minerals and rocks into groups of similar composition and assign a reference code. Table 5.b.3 and Table 5.b.4 list the minerals and rocks in alphabetical order along with the matrix values and hierarchical code.

Rocks and minerals may be easily located and cross-referenced with members of the same group.

Note: References in this task have been assigned a letter rather than listed in alphabetical order. This allows simplification of listings given in Tables 5.b.3 and 5.b.4.

TABLE 5.b.1: HIERARCHICAL RELATIONSHIP OF MINERALS

1. ORTHO- & RING SILICATES

1.1 OLIVINE GROUP

- 1.1.1 Olivine: $(Mg,Fe)_2[SiO_4]$
  - 1.1.1.1 Forsterite: Mg_2SiO_4
  - 1.1.1.2 Fayalite: Fe_2SiO_4

2. CHAIN SILICATES

2.1 PYROXENE GROUP

- 2.1.1 Enstatite-Orthoferrosilite: $(Mg,Fe^{+2})[SiO_3]$
  - 2.1.1.1 Enstatite/Clinoenstatite: $Mg_2Si_2O_6$
  - 2.1.1.2 Orthoferrosilite/Clinoferrosilite: $Fe_2Si_2O_6$
- 2.1.2 Diopside-Hedenbergite: $Ca(Mg,Fe)[Si_2O_6]$
- 2.1.3 Augite-Ferroaugite: $(Ca,Na,Mg,Fe^{+2},Mn,Fe^{+3},Al,Ti)_2$ $[(Si,Al)_2O_6]$

3. SHEET SILICATES

3.1 MICA GROUP

- 3.1.1 Muscovite: $K_2Al_4[Si_6Al_2O_{20}](OH,F)_4$
- 3.1.2 Glauconite: $(K,Na,Ca)_{1.2-2.0}(Fe^{+3},Al,Fe^{+2},Mg)_{4.0}$ $[Si_{7-7.6}Al_{1-0.4}O_{20}](OH)_4 \cdot n(H_2O)$
- 3.1.3 Phlogopite: $K_2(Mg,Fe^{+2})_6[Si_6Al_2O_{20}](OH,F)_4$
  - 3.1.3.1 Eastonite: $K_2Mg_5Al[Si_5Al_3O_{20}](OH)_4$
- 3.1.4 Biotite: $K_2(Mg,Fe^{+2})_{6-4}(Fe^{+3},Al,Ti)_{0-2}[Si_{6-5}Al_{2-3}O_{20}]$ $(OH,F)_4$
  - 3.1.4.1 Annite: $K_2Fe_6[Si_6Al_2O_{20}](OH)_4$
  - 3.1.4.2 Siderophyllite: $K_2Fe_5Al[Si_5Al_3O_{20}](OH)_4$

3.2 CHLORITE/SEPTECHLORITES

3.2.1 Chlorite: $(Mg,Al,Fe)_{12}[(Si,Al)_8O_{20}](OH)_{16}$

3.2.1.1 Daphnites: $(Fe_4Al_2)[(Si_2Al_2)O_{10}](OH)_8$

3.2.2 Septechlorite: $Y_6[Z_4O_{10}](OH)_8$

3.2.2.1 Amesite: $(Mg_4Al_2)[(Si_2Al_2)O_{10}](OH)_8$

3.2.3 Serpentine: $Mg_3[Si_2O_5](OH)_4$

3.2.3.1 Antigorite: $Mg_3[Si_2O_5](OH)_4$

3.2.3.2 Ferroantigorite: $Fe_3[Si_2O_5](OH)_4$

3.3 CLAY MINERALS

3.3.1 Kaolinite Group: $Al_4[Si_4O_{10}](OH)_8$

3.3.2 Illite: $K_{1-1.5}Al_4[Si_{7-6.5}Al_{1-1.5}O_{20}](OH)_4$

3.3.3 Montmorillorite Group: $(1/2Ca,Na)_{0.7}(Al,Mg,Fe)_4$
$[(Si,Al)_8O_{20}](OH)_4.nH_2O$

4. FRAMEWORK SILICATES

4.1 FELDSPAR GROUP

4.1.1 Alkali Feldspars: $(K,Na)[AlSi_3O_8]$

4.1.1.1 Orthoclase: $KAlSi_3O_8$

4.1.2 Plagioclase Feldspars: $Na[AlSi_3O_8]-Ca[Al_2Si_2O_8]$

4.1.2.1 Albite: $NaAlSi_8O_8$

4.1.2.2 Anorthite: $CaAl_2Si_2O_8$

4.2 SILICA MINERALS

4.2.1 Quartz: SiO_2

4.2.1.1. Quartz: SiO_2

4.2.1.2 Opal: $SiO_2.nH_2O$

4.2.1.3 Chert: SiO_2

4.2.1.4 Flint: SiO_2

4.3 ZEOLITE GROUP

4.3.1 Zeolites: $(Na_2,K_2,Ca,Ba)[Al,Si)O_2]n.xH_2O$

5. NON-SILICATES

5.1 OXIDES

5.1.1 Hematite: Fe_2O_3

5.1.2 Ilmenite: $FeTiO_3$

5.1.3 Spinel Group

5.1.3.1 Magnetite: $Fe^{+2}Fe_2{}^{+3}O_4$

5.2 HYDROXIDES

5.2.1 Limonite: $2FeO_3 \cdot 3H_2O$

5.3 SULFIDES

5.3.1 Pyrite: FeS_2

5.3.2 Pyrrhotite: Fe_nS_{n+1}

5.4 SULFATES

5.4.1 Barite: $BaSO_4$

5.4.2 Celestite: $SrSO_4$

5.4.3 Gypsum: $CaSO_4 \cdot 2H_2O$

5.4.4 Anhydrite: $CaSO_4$

5.4.5 Langbeinite: $K_2SO_4 \cdot 2MgSO_4$

5.4.6 Polyhalite: $K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$

5.4.7 Kainite: $KMg(SO_4)Cl \cdot 3H_2O$

5.4.8 Kieserite: $MgSO_4 \cdot H_2O$

5.5 CARBONATES

5.5.1 Calcite: $CaCO_3$

5.5.2 Siderite: $FeCO_3$

5.5.3 Dolomite: $CaMg(CO_3)_2$

5.5.4 Aragonite: $CaCO_3$

5.5.5 Trona: $Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$

5.5.6 Nahcolite: $NaHCO_3$

5.6 PHOSPHATES

5.6.1 Cellophane: $Ca_3(PO_4)_2-H_2O$

5.6.2 Dahllite: $Ca_5(PO_3)_{3-X}(CO_3OH)_XOH$

5.7 BORATES

5.7.1 Kernite: $Na_2B_4O_6(OH)_2.3H_2O$

5.8 HALIDES

5.8.1 Halite (Salt): NaCl

5.8.2 Sylvite: KCl

5.8.3 Carnallite: $KCl.MgCl_26H_2O$

5.9 NATIVE ELEMENTS

5.9.1 Sulfur: S_8

5.9.a Graphite: C

5.10 COAL

5.10.1 Lignite:

5.10.2 Bituminous Coal:

5.10.3 Anthracite Coal:

TABLE 5.b.2: HIERARCHICAL RELATIONSHIP OF ROCKS

1. SEDIMENTARY ROCKS

1.1 CLASTICS

1.1.1 Sandstone (Primarily quartz)

1.1.1.1 Unconsolidated

1.1.1.2 Consolidated

1.1.2 Siltstone (Primarily quartz, very fine grained)

1.1.3 Shale (Primarily clay minerals and fine-grained quartz)

1.1.4 Greywacke

1.2 NON-CLASTICS

1.2.1 Limestone (Primarily Calcite)

1.2.2 Dolomite (Primarily Dolomite)

1.3 VOLCANIC DEBRIS

1.3.1 Volcanic Ash (Composition variable)

1.3.2 Tuff (Composition Variable)

2. IGNEOUS ROCKS (See Figure 5.b.1)

2.1 GRANITE-RHYOLITE FAMILY

2.1.1 Plutonic Class

2.1.1.1 Granite

2.1.1.2 Granodiorite

2.1.1.3 Syenite

2.1.1.4 Monzonite

2.1.2 Volcanic Class

2.1.2.1 Rhyolite

2.1.2.2 Obsidian

TABLE 5.b.2: HIERARCHICAL RELATIONSHIP OF ROCKS

2.2 DIORITE-ANDESITE FAMILY

- 2.2.1 Plutonic Class
  - 2.2.1.1 Diorite
- 2.2.2 Volcanic Class
  - 3.3.3.1 Andesite

2.3 GABBRO-BASALT FAMILY

- 2.3.1 Plutonic Class
  - 2.3.1.1 Gabbro
  - 2.3.1.2 Norite
  - 2.3.1.3 Diabase
  - 2.3.1.4 Dunite
  - 2.3.1.5 Anorthosite
- 2.3.2 Volcanic Class
  - 2.3.2.1 Basalt

3. METAMORPHIC ROCKS (See Figure 5.b.2)

Figure 5.b.1

Diagram showing order or crystallization of the common rock-forming minerals.

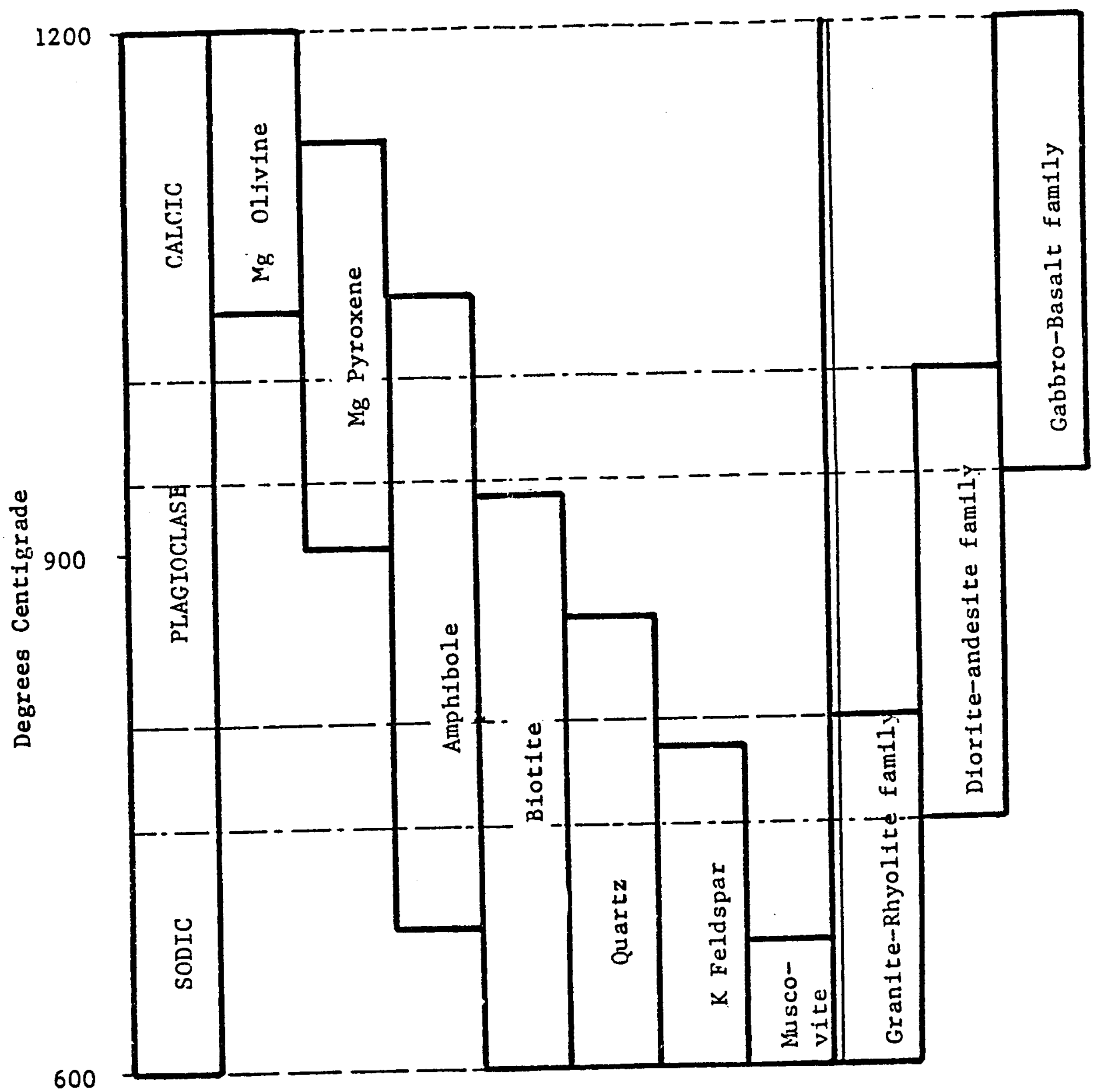
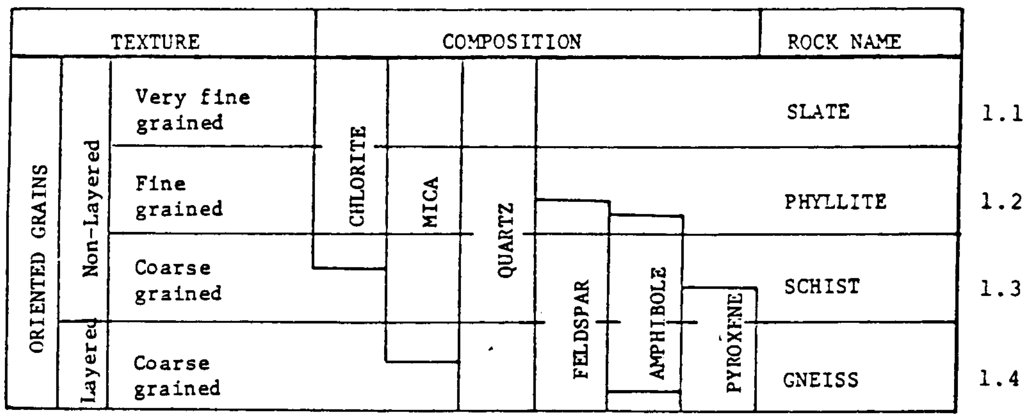


Figure 5.b.2

Classification of metamorphic rocks.

1. FOLIATED



2. NON-FOLIATED

TEXTURE	COMPOSITION	ROCK NAME	
Coarse grained	Deformed Fragments of Any Rock Type	META-CONGLOMERATE	2.1
Fine to Coarse grained	Quartz	QUARTZITE	2.2
	Calcite or Dolomite	MARBLE	2.3

TABLES OF MATRIX AND RESPONSE VALUES

The following two tables are listings of the matrix and response values for density, sonic, and neutron logs.

TABLE 5.b.3: Values for Minerals as classified in TABLE 5.b.1.

TABLE 5.b.4: Values for Rocks as classified in TABLE 5.b.2.

EXPLANATION OF TABLES 5.b.3 & 5.b.4

MINERAL/ROCK and CODE Column.

This column lists the name of the mineral or rock in alphabetical order. Below the name is the code for the hierarchical relationship as given in TABLES 5.b.1 & 5.b.2.

DENSITY Column.

The density column may have up to five rows of data. Unit for all rows is grams per cubic centimeter.

Row 1: Specific Gravity and reference source.

Row 2: Range of Specific Gravity and reference source. If a number is listed in place of a reference letter, the reference is the same as the row immediately above. The number is the quantity of samples from which the range of values were derived.

Row 3: Apparent matrix density based on a tool calibration with Z/A ratio of 0.5. (Refer to reference F for additional explanation.) When no reference was found for this row, a value was computed from the chemical formula and the Specific Gravity in Row 1. If this average value was not available, the apparent matrix density was computed using the mid-value of the range given in Row 2.

Row 4: Actual log reading of rock or mineral.

Row 5: Apparent matrix values as determined by charts or crossplots. Method used noted with reference.

SONIC Column.

The sonic column may have up to five rows of data.

Row 1: Average matrix travel time in microseconds per foot and reference source.

Row 2: Range of matrix travel time and reference source. If a number is listed in place of a reference letter, the reference is the same as the row immediately above. The number is the quantity of samples from which the range of values were derived.

Row 3: The average matrix travel time in microseconds per meter.

NOTE: Laboratory measurements given may have been made at Standard Temperature and Pressure or at simulated overburden pressure. The difference may be significant. Refer to individual listing and Reference R.

Row 4 &
Row 5: Same as described for density column, except sonic data is listed. Units are microseconds per foot.

NEUTRON Column.

The neutron column may list either a value or a range in Row 1 in percentage units. Of the three responses listed, the neutron response varies with tool type more than the others. For the most part, neutron tools may be grouped in three classes.

A. Thermal neutron - single detector - large hole size effect - moderate matrix effect.

B. Thermal neutron - dual detector, compensated - small hole size effect - greatest matrix effect.

C. Epithermal neutron - single detector, pad type - small hole size effect - low matrix effect.

To determine the neutron response for all the neutron classes and tool configurations would be a monumental undertaking. A method of computing a rough estimate, based strictly on hydrogen content, is described in Reference B. Where possible, a note is made with the reference as to the particular tool, class, or estimation from hydrogen content. When individual commercial tool is listed, the response is given in limestone units.

Rows 4 and 5 are the same as described for density column, except neutron data is listed in percentage units.

DENSITY-SONIC-NEUTRON MATRIX PARAMETERS

MINERAL AND CODE	DENSITY		SONIC		NEUTRON		ROW
ALBITE	2.62	B	50.2	B	- .5	L	1
4.1.2.1	2.61-2.65	B	49.5-50.6	B			2
	2.56	B	164.7				3
			55.1	H			1
			180.8				2
	2.62	N	49.2	N			1
	2.61-2.63	2	42.0- 69.6	11			2
			161.4				3
	2.63	P	47.2	P			1
			154.8				3
ANHYDRITE			50	C	0	T	1
5.4.4	2.89-2.98	A					2
	2.977	C	164.0				3
	2.928	N	51.8	N			1
			48.1-63.5	4			2
			170.0				3
ANORTHITE	2.76	A	45.4	B	- 1.2	L	1
4.1.2.2	2.60	E					3
ARAGONITE	2.917	N	53.5	N			1
5.5.4			175.4				2
AUGITE	3.26	N	81.6	N	0.3- 1.3	L	1
2.1.3	3.2 -3.4	A	57.5-103.3	3			2
	3.23	E	267.6				3
BARITE	4.45	B					1
5.4.1	4.3 -4.6	B					2
	3.96	B					3

TABLE 5.B.3, PAGE 1

DENSITY-SONIC-NEUTRON MATRIX PARAMETERS

MINERAL AND CODE	DENSITY		SONIC		NEUTRON		ROW
BIOTITE	2.9	B	50.8	N	6.0	B	1
3.1.4	2.65-3.1	B	39.1- 72.4	2			2
	2.84	B	166.5				3
	3.05	N		L	13 -15.5		1
CALCITE	2.71	A	47.5	C	0	T	1
5.5.1	2.71	C	155.8				3
	2.70	N	49.2	N			1
			42.8- 63.5	S			2
			161.4				3
CARNALLITE	1.61	C	78	C	65	C	1
5.8.3	1.57	C	255.9				3
			83.3	B			1
			273.3				3
CELESTITE					- 0.5	L	1
5.4.2	3.95-3.97	A					2
	3.71	E					3
CHLORITE	2.71	B			32	B	1
3.2.1	2.60-3.22	B					2
	2.74	B					3
					26 -54	L	1
COAL, ANTHRACITE	1.60	B	105	B	40	B	1
5.10.3	1.32-1.80	B	90 -120	B			2
	1.64	B					3

TABLE 5.8.3, PAGE 2

DENSITY-SONIC-NEUTRON MATRIX PARAMETERS

MINERAL AND CODE	DENSITY		SONIC		NEUTRON		ROW
COAL, BITUMINOUS	1.35	B	120	B	66	B	1
5.10.2	1.15-1.7	B	100 -140	B			2
	1.4	B					3
DIOPSIDE	3.2	A					1
2.1.2	3.08	N	54.9	N			1
			40.7- 90.7	3			2
	3.07	E	180.0				3
DOLOMITE	2.85	A	43.5	C	4	T	1
5.5.3	2.876	C	142.7				3
	2.784	N	58.3	N			1
	2.58-2.83	5	50.3-66.8	4			2
			191.3				3
FAYALITE	4.39	A			2.0	L	1
1.1.1.2	4.22	E					3
FORSTERITE	3.2	A			1.6	L	1
1.1.1.1	3.19	E					3
GLAUCONITE	2.30	B			19	B	1
3.1.2	2.20-2.80	B					2
	2.30	B					3
					31 -40	L	1
GRAPHITE	2.23	A					
	2.04-2.23	B					
	2.23	B					

TABLE 5.8.3, PAGE 3

SCIENTIFIC SOFTWARE CORPORATION

DENSITY-SONIC-NEUTRON MATRIX PARAMETERS

MINERAL AND CODE	DENSITY		SONIC		NEUTRON		ROW
GYPSUM	2.32	A	52.5	C	49	T	1
5.4.3	2.351	C	172.2				3
HALITE	2.16	C	67	C	0	C	1
5.8.1	2.03	C	219.8				3
HEMATITE	5.26	B	42.9	H	2.5	L	1
5.1.1	4.9 -5.3	B					2
	5.04	B	140.7				3
	5.21	N	44.2	N			1
	4.93-5.5	2	42.9- 46.3	4			2
			145.1				3
	4.93	P	44.7	P			1
			146.6				3
ILLITE	2.84	B			37	B	1
3.3.2	2.6 -3.0	B					2
	2.81	B					3
					20 -30	L	1
	2.58-2.65	L					2
ILMENITE	4.75	B			6.5	L	1
5.1.2	4.5 -5.0	B					2
	4.52	B					3
KAINITE	2.13	C			45	C	1
5.4.7	2.12	C					3

TABLE 5.8.3, PAGE 4

DENSITY-SONIC-NEUTRON MATRIX PARAMETERS

MINERAL AND CODE	DENSITY		SONIC		NEUTRON		ROW
KAOLINITE	2.63	B			37	B	1
3.3.1	2.4 -2.68	B					2
	2.68	B					3
					51	L	1
KERNITE	1.91	B	50.0	B	50	B	1
5.7.1	1.92	B	164.0				3
KIESERITE	2.57	A			31	B	1
5.4.8	2.43	E					3
LANGBEINITE	2.83	B	52	B	0	C	1
5.4.5	2.81	E	170.6				3
LIGNITE	1.1	B	160	B	HIGH		1
5.10.1	0.5 -1.5	B	140 -180	B			2
	1.16	B					3
LIMONITE	3.8	B	56.9	N	55	B	1
5.2.1	3.51-4.0	B	56.2- 57.7	3			2
	3.72	B	186.7				3
	3.55	N					1
MAGNETITE	4.73	N	74.6	N	3.5	L	1
5.1.3.1	4.53-4.86	6	51.7-132.5	6			2
	4.52	E	244.6				3
	4.81	P	72.9	P			1
			239.2				3
	5.18	B					1
	4.97-5.18	B					2
	4.95	B					3

TABLE 5.8.3, PAGE 5

DENSITY-SONIC-NEUTRON MATRIX PARAMETERS

MINERAL AND CODE	DENSITY		SONIC		NEUTRON		ROW
MONTMORILLONITE	2.35	B			17	B	1
3.3.3	2 -3	B					2
	2.35	B					3
MUSCOVITE	2.93	B	48.9	N	13.0	B	1
3.1.1	2.76-3.1	B	38.0-68.6	2			2
	2.91	B	160.4				3
	2.83	L			14.5	L	1
	2.79	N					1
	2.77	E					3
NAHCOLITE	2.20	B			24	B	1
5.5.6	2.16	B					3
OLIVINE	3.32	N	34.8	N	1.6- 2.0	L	1
1.1.1	3.27-4.37	A	30.9- 39.4	3			2
			114.3				3
OPAL			58.0	H	8	D	1
4.2.1.2	2.0 -2.25	A					2
	2.15	D	190.3				3
			57.9	N	5 -13	L	1
ORTHOCLASE	2.57	B	69.1	H	- 1.8	L	1
4.1.1.1	2.55-2.63	B					2
	2.55	B	226.7				3
			69.2	N			1
			53.3- 80.2	3			2
			226.9				3

TABLE 5.8.3, PAGE 6

DENSITY-SONIC-NEUTRON MATRIX PARAMETERS

MINERAL AND CODE	DENSITY		SONIC		NEUTRON		ROW
PHLOGOPITE 3.1.3	2.81	N	49.8	N			1
			38.3- 71.2	2			2
			163.4				3
POLYHALITE 5.4.6	2.78	B	57.5	B	17	B	1
	2.79	B	188.6				3
					15	C	1
PYRITE 5.3.1	4.88	N	39.2	N	- 6.7	L	1
	4.81-5.02	7	35.0- 42.2	12			2
	4.74	E	128.5				3
	4.81	P	39.6	P			1
			130.0				3
	5.06	B					1
	4.95-5.17	B					2
	4.91	B					3
PYRRHOTITE 5.3.2	4.55	N	65.0	N	- 7.	L	1
	4.58-4.65	A	64.7- 65.4	3			2
	4.40	B	213.2				3
	4.55	P	65.0	P			1
			213.2				3
QUARTZ 4.2.1.1	2.65	A	51.5	C	- 4	T	1
	2.648	C	169.0				3
SERPENTINE 3.2.3	2.3 -2.6	A					1
	2.694	N	54.4	N			1
	2.50-2.89	18	43.2- 91.3	17			2
	2.66	E	178.4				3

TABLE 5.B.3, PAGE 7

DENSITY-SONIC-NEUTRON MATRIX PARAMETERS

MINERAL AND CODE	DENSITY		SONIC		NEUTRON		ROW
SIDERITE 5.5.2	3.8 3.67	A E			4.5	L	1 3
SULFUR 5.9.1	2.05-2.09 2.03	A C	122 400.3	C	0	S	1 2 3
SYLVITE 5.8.2	1.984 1.863	C C	74.0 242.8	C	0	C	1 3

TABLE 5.8.3, PAGE 8

DENSITY-SONIC-NEUTRON MATRIX PARAMETERS

ROCK AND CODE	DENSITY		SONIC		NEUTRON		ROW
BASALT			54	G	7	G	1
2.3	3.03	G	177.2				3
	2.55	N	61.1	N			1
	2.0-3.0		47.0-101.9	20			2
			200.4				3
	2.97	P	51.1	P			1
			167.8				3
	2.69	P	56.8	P			1
			186.2				3
	2.73		54.8	P			1
			179.9				3
BYTOWNITE	2.71	N	44.0	N			1
			41.4- 45.6	3			2
			144.3				3
CALCITE MARBLE	2.77	J	49.5	J	0	J	4
2.3	2.77		49.5				5
CONGLOMERATE-BRECCIA	2.75	I	57.2	I			1
MOSAIC IN GRANITE			187.7				3
MATRIX-TIGHTLY CLOSED	2.78	I	58.4	I			1
FRACTURES			191.6				3
2.1.1.1							
COPROLITE	2.4 -2.65	Q	50 - 55	Q	0	Q	1
4.2.1							

TABLE 5.B.4, PAGE 1

DENSITY-SONIC-NEUTRON MATRIX PARAMETERS

ROCK AND CODE	DENSITY	SONIC	NEUTRON	ROW
DIABASE	2.98 B	44.6 B		1
2.3.1.3	2.96-3.05 6	44 - 46 B		2
	2.95 B	146.3		3
		43.8 M		1
		143.9		3
	2.998 N	47.7 N		1
		38.9- 59.2 15		2
		156.5		3
	2.97 P	51.1 P		1
		167.8		3
DOLOMITE MARBLE	2.825 J	43.5 J	0 J	4
2.3	2.825	43.5		5
DUNITE	3.3 B	38.2 B		1
2.3.1.4	3.24-3.74 4	34.7- 41.1 B		2
	3.29 B	125.3		3
		37.9 M		1
		124.3		3
	3.30 N	42.2		1
	2.96-3.76 34	36.7- 55.8 29		2
		138.3		3
	3.25 P	48.0 P		1
		157.5		3

TABLE 5.8.4, PAGE 2

DENSITY-SONIC-NEUTRON MATRIX PARAMETERS

ROCK AND CODE	DENSITY	SONIC	NEUTRON	ROW
GABBRO 2.3.1.1	2.976 B	42.4 B		1
	2.85-3.12 27	42.2- 47.6 B		2
	2.94 B	139.1		3
		43.7 M		1
		143.3		3
	2.95 N	47.6		1
	2.8 -3.05 9	44.3- 52.6 5		2
		156.2		3
GABBRO WITH FRACTURES 2.3.1.1	3.00 I	46.7 I		1
		153.2		3
FRACTURED GRANODIORITE GABBRO	2.89 I	47.3 I		1
		155.2		3
GNEISS, DARK AND POORLY BANDED 1.4	3.04 I	54.7 I		1
		179.5		3
GNEISS, GRANITIC, PINK TO GRAY 1.4	2.75 I	48.6 I		1
		159.4		3
GNEISS, GRAY, LIGHT TO MEDIUM 1.4	2.80 I	48.3 I		1
		158.5		3
GNEISS, GRAY TO GREENISH-GRAY 1.4	2.83 I	45.5 I		1
		149.3		3

TABLE 5.B.4, PAGE 3

DENSITY-SONIC-NEUTRON MATRIX PARAMETERS

ROCK AND CODE	DENSITY		SONIC		NEUTRON		ROW
GRANITE	2.667	B	50.8	B			1
2.1.1.1	2.52-2.81	155	46.8- 53.5	B			2
	2.65	B	166.7				3
			64.9	M			1
			53.5- 76.3	M			2
			212.9				3
	2.68	N	56.2	N			1
	2.45-2.94	63	42.6- 82.4	67			2
			184.5				3
GRANITE, GRAY TO PINK	2.88	I	42.6	I			1
2.1.1.1			139.8				3
GRANITE, MED GRND.	2.62	I	55.1	I			1
QTZ FILLED FRACTURES			180.8				3
2.1.1.1							
GREYWACKE	2.705	N	52.9	N			1
1.1.4			49.2- 56.4	4			2
			173.6				3
LABRADORITE	2.683	N	43.3	N			1
			38.1- 50.3	18			2
			142.1				3
MICA SCHIST	2.79	K	60.0	K	6.5	K	4
1.3	2.83		49.5				5

TABLE 5.8.4, PAGE 4

DENSITY-SONIC-NEUTRON MATRIX PARAMETERS

ROCK AND CODE	DENSITY	Ref.	SONIC	Ref.	NEUTRON	Ref.	ROW
NORITE	2.984	B	44.1	B			1
2.3.1.2	2.72-3.02	11	43.5- 49.0	B			2
	2.97	B	144.7				3
	2.96	N	47.2	N			1
	2.85-3.08	8	46.2- 49.3	5			2
	2.95	E	154.9				3
OBSIDIAN	2.35	P	52.4	P			1
2.1.2.2			171.8				3
	2.35	P	52.1	P			1
			170.9				3
OLIGOCLASE	2.64	N	48.2	N			1
			35.6- 55.6	18			2
			158.1				3
PHYLLITE	2.79	J	58.5	J	8	J	4
1.2	2.89		47.5				5
QUARTZITE			55.1	N			1
2.2			46.2- 92.4	14			2
			180.6				3
	2.70	J	53.5	J	- 1.5	J	4
	2.68		54.5				5
QUARTZ MONZONITE	2.64	N	56.5	N			1
2.1.1.4	2.63-2.65	4	52.4- 59.8	3			2
			185.4				3

TABLE 5.8.4, PAGE 5

DENSITY-SONIC-NEUTRON MATRIX PARAMETERS

ROCK AND CODE	DENSITY	SONIC	NEUTRON	ROW
RHYOLITE	2.39 P	74.3 P		1
2.1.2.1		237.0		3
	2.05 P	93.2 P		1
		305.8		3
	2.258 N	72.9 N		1
		43.6- 96.5 3		2
		239.1		3
TRONA	2.125 B	65.0 B	42 B	1
5.5.5	2.11-2.15 B			2
	2.14 B	213.2		3
	2.12 C		40 C	1
	2.10 C			3
TUFF	1.38 P	213.1 P		1
1.3.2		699.1		3
ASH-FLOW TUFF	2.69 I	62.8 I		1
1.3.2		206.0		3
DEVITRIFIED TO ARGILL-IZED, PARTIALLY TO DENSELY WELDED TUFF	2.56 I	59.8 I		1
1.3.2		196.2		3
ZEOLITIZED BEDDED TUFF	2.58 I	63.5 I		1
1.3.2		208.3		3
VOLCANIC BRECCIA	2.19 P	72.2 P		1
1.3		237.0		3

TABLE 5.8.4, PAGE 6

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Well	- R.R.G.E. #2
Field	- Raft River Geothermal
County	- Cassia
State	- Idaho

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S. A neutron response in pure sulfur (near zero) may be quite different than the end-point value necessary for resolving the mixture of sulphur and other minerals. For more information, review References C and T.

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Subtask C: Fracture Delineation

This subtask calls for evaluation of the various techniques for detecting and evaluating the characteristics of fractures from well logs. In the next two quarters, we shall critically evaluate the various fracture-detection techniques.

A single, reliable interpretation technique for detecting and evaluating fracture systems has not been developed. Many techniques are in daily use with success but may be limited to a particular field or type of formation. Aguilera and VanPoolen (1977) list eight different methods for approaching the problem and 214 references. Thirty-two of these references are related to log-analysis techniques.

Of the many log-analysis techniques available, the most difficult problem is determining which method to use. Local experience is the best key to success in this situation. Exploratory wells may present an evaluation problem if only limited data are available. The following are brief discussions of several techniques or log characteristics which may be used to detect fractures.

The definition of a fracture system involves the location of the fractures (the depth at which the fractures occur), the width of the fracture (the aperture), and the orientation of the fracture (whether it is horizontal or vertical, the degree of dip, or the azimuth). It is also important to know if the fracture is open or plugged with solids such as precipitates from geothermal water or swelling clay, etc. The easiest and the first indication of fractures in a well as it is being drilled is a sudden increase in the rate of drilling. Also, if drilling mud is used, it is likely that fracture zones will cause significant lost circulation compared to the non-fractured zones in the well. Thus, the drilling record of the well can sometimes be used to delineate the existing fracture systems in the well. Similarly the drill-cutting log, which is a description of the drill cuttings obtained continuously as the well is drilled, can be useful in identifying fractures. For example, in the Roosevelt Hot Springs field in Utah, the fracture systems are normally associated with the development of quartz crystals ("drusy" quartz) on the fracture surface (Crosby, personal communication, 1976). Thus when drilling a well in this field, the occurrence of "drusy" quartz in drill cuttings is an indication that the drill bit has reached a fracture system.

Various well logs can indicate the location of fracture zones and can be used to understand the fracture characteristics. For example, the caliper log provides the diameter of the well bore with depth. Whenever there are fractures in the well, it is likely that the diameter of the well bore will be larger at the depth of the fractures. Thus a caliper log can indicate location of fractures. The six-arm caliper log can be used to estimate the dip of the fracture. Temperature logs can indicate fractures by perturbation in the temperature profile in the well bore. For example, if a newly drilled well produces hot water or steam through a fracture system at a certain depth, the temperature at that depth is likely to be higher than that expected from the general temperature gradient in the well which is partially cooled due to mud circulation. On the other hand, during back flow of an injection well, the temperature at the points where injection water enters the formation will be lower than that expected from the general temperature gradient in the well.

There are several commercial logs which are useful for finding fractures, for example, the so-called Fracture Finder log, Microseismogram log, etc. These logs are based on transmission of sonic waves through the formation. Sonic wave amplitude is affected by the presence of fractures. Both shear and compressional wave amplitudes can be measured and be used to analyze the fracture characteristics. A full-wavetrain sonic log can indicate the presence of fractures, such as had been used successfully in the Los Alamos Hot Dry Rock Project. The sonic velocity log can be used to obtain an approximate estimate of the amount of fracture porosity in a formation. For example, in an otherwise dense formation, the presence of isolated fractures will not affect the sonic travel times as presented on the log, whereas other porosity logs such as density and neutron are affected by the presence of fractures. Hence, the difference between the porosity as calculated from a density log and the porosity as obtained from a sonic log gives an approximate value of the amount of the fracture porosity in the formation. Another type of sonic device useful for locating and understanding fracture systems is the borehole televiewer log. This log gives the "picture" of the fracture at the wellbore surface. From this picture, one can obtain the location, width, orientation, and shape of the fracture. Thus a borehole televiewer log is the most "visible" fracture evaluation method. Until recently, however, the borehole televiewer log was not available for geothermal wells because of the temperature limitations of the logging tool. Recently, the United States Geological Survey, Keys (1978), developed a borehole televiewer tool that can perform up to very high temperatures on the order of 204°C (400°F) and provide reliable "pictures" of fractures. Borehole televiewer logs using this equipment have been obtained successfully in various geothermal systems, such as the Los Alamos Hot Dry Rock Project, Raft River Geothermal Field in Idaho, the Roosevelt Hot Springs Field in Utah, etc.

Electrical logs of various kinds can be used to obtain information about fracture systems in a well. For example, self-potential logs can show fractures in an otherwise massive formation by indicating the presence of streaming potential in a well. Usually, in a massive formation such as those encountered in the Los Alamos wells, the self-potential log does not provide any meaningful data except in fracture zones where self-potential consists primarily of the streaming potential. In a massive formation, electrical resistivity is practically infinite. However, when there are fractures, the water content in the fracture reduces the formation resistivity. Hence, resistivity logs can indicate the presence of fractures by a sudden lowering of resistivity. The single point resistivity is especially sensitive to rock geometry. A combination of deep and shallow investigation resistivity devices can be used effectively to obtain some idea about orientation of fractures around the wellbore. Another possible approach to determining the presence of fractures from electrical logs is to plot the formation resistivity factor as obtained from the resistivity log versus the porosity of the formation on log/log paper, and then determine the slope of the line that fits the data. The principle here is that if the formation has intergranular porosity, the slope of that line is approximately two. Whereas, if it is a uniformly spaced fracture system, the slope of the line is of the order of one. Thus the slope of the formation resistivity factor vs porosity line could be utilized as a fracture indicator.

The short-spaced detector of dual-spaced compensated density logs may be more influenced by a nearby fracture than the longer spacing. If the borehole is smooth and without a mudcake, fractures may cause a larger correction than would be expected.

Tools commonly used for measuring dip data are successfully used in locating fractures. Being heterogeneous around the borehole, a fracture crossed by one of the micro-resistivity pads will cause a much lower reading than a pad reading unfractured dense rock. In addition, orientation of the fracture can be determined if the fracture is encountered by more than one pad.

Computation of Bulk Modulus from sonic and density logs may locate the more dense, brittle rock more likely to have fractures.

West and Laughlin (1976) related increases in uranium content with fractures from the Spectral Gamma Ray log in the LASL GT-2 well.

It should be noted that for each of the fracture-detection techniques listed, two other possibilities can occur and have been observed.

1. Fractures are indicated but do not exist.

2. Fractures are not indicated but do exist.

These potential discrepancies explain the advantage of experience and knowledge of the formation under evaluation. The exploratory well must be evaluated with all available techniques in order to locate fractures.

The Fenton Hill GT-2 well, discussed in Task 4, was evaluated for fractures using a multi-technique system. Five techniques were used to sum up the term "FRAC".

1. Resistivity
2. Hole washout
3. Excess density correction in gauge hole
4. Comparison of sonic porosity with porosity from neutron and density
5. Mechanical properties (using sonic and density)

Each individual test which indicated fractures added a value of 1 to FRAC, giving a range of 0 to 5. The larger the term FRAC, the greater the likelihood for the existence of fractures. An analog playback of this term is included in Figure 4.16.

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Subtask D: Temperature Transient Analysis

This subtask calls for evaluating the various temperature transient analysis techniques and associated temperature log data. As a first step toward this, we have completed a literature search which revealed that the body of literature on this topic can be broadly grouped into five categories.

Conductive Models - In these approaches, the well bore is considered a cylindrical source (or sink) of conductive heat. No fluid movement radially outward from the well is considered.

Fluid Loss Models for Fractures - These approaches consider the convective heat flow due to loss of fluid during drilling or injected water in fractures.

Fluid Loss Models for Porous Zones - The same as above category, except that porous formation rather than a fracture is present.

Injection Profile Estimation - These papers deal with the prediction and interpretation of water (or gas) injection profiles from temperature logs.

General Temperature Log Interpretation - There are a large number of papers dealing with various other aspects of temperature log interpretation.

A list of the collected references under these categories follows.

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SUMMARY

The interpretation of geothermal well logs is made more difficult for two primary reasons. First, securing sufficient quality data may be difficult because of several factors. Temperature limitations of downhole equipment may prevent the recording of essential surveys. Incomplete logging suites may be run by choice or due to borehole conditions. Well logs may be run but often produce poor quality data due to the borehole environments. Economics may preclude the running of well logs, coring, cuttings examination or other techniques used to gather data. These situations, and others, hinder the development of interpretation techniques in areas where present methods produce usable answers.

Second, the interpretation techniques commonly used in the petroleum industry are not, in many cases, sufficient to identify or define the desired formation characteristics. The classification of geothermal reservoirs (Task 2) defines four physical properties (plus geologic province) which may vary and require different interpretive approaches. These are fluid phase and temperature, lithology, pore geometry, and fluid chemistry.

The survey of the State of The Art (Task 1) and the example computations shown in Task 4 - Problem definition, demonstrate the need for interpretation development in the following areas.

1. Determination of porosity and lithology in complex formations (igneous, metamorphic and volcanics) is needed for both geologic and reservoir evaluation. For the most part, the computation of porosity is not possible without knowledge of the formation lithology. The evaluation of lithology is currently hampered by lack of special rock-tool

calibrations (of the matrix response to currently used calibrations) and the interpretation techniques used with the available logs. Inroads into these problems have been made (see Task 5b-Matrix response) and further studies are being made into computer processing and cross plot techniques.

2. Pore geometry interpretation models and the detection and evaluation of fractures are two related problems which still plague the petroleum industry and appears to be even more important to the geothermal industry. Relationships such as the Formation Resistivity Factor are greatly influenced by pore geometry and fractures and will require further study for reliable definition. Task 5c covers the many techniques currently used for fracture detection and the problems associated with their use. Studies should show which techniques or combinations of techniques will provide the most reliable answers for particular geological areas or rock types.

3. Thermal evaluation of geothermal reservoirs may be improved immediately with better record keeping during logging operations. Bottom hole temperature measurements on each logging operation along with accurate time data between operations and bore hole fluid circulations are valuable for estimating true formation temperature. Various types of temperature interpretation techniques have been surveyed (Task 5d) and models are being developed for testing with available temperature logs. In conjunction with temperature evaluation studies, the detection of thermal alteration from matrix characteristics is being researched on several East Mesa wells.

APPENDIX A

DESCRIPTION OF M-N PLOTS

Note: M-N PLOT is a trademark of Schlumberger.

The values M and N were developed to facilitate the study of lithology from the sonic, neutron, and density logs. The equations for M and N are shown in Figure A-1 on the crossplots relating to their application. Plots A and B are basic porosity crossplots identical in units to the actual computer crossplots shown in Figures 4.1 and 4.3. However, Plots A and B are extended to include the 100% water or fluid point.

The primary characteristic of M and N is that all pairs of points which fall on a linear lithology line, regardless of porosity, will have the same value of M or N. For example, limestone will have the values M = 0.817 and N = 0.585 regardless of porosity value. Other lithologies, having a different matrix point, will resolve their own characteristic values of M and N.

The resulting two-dimensional crossplot (see Figure 4.4) combines data from three logs and reflects primarily the lithology with little influence of formation porosity.

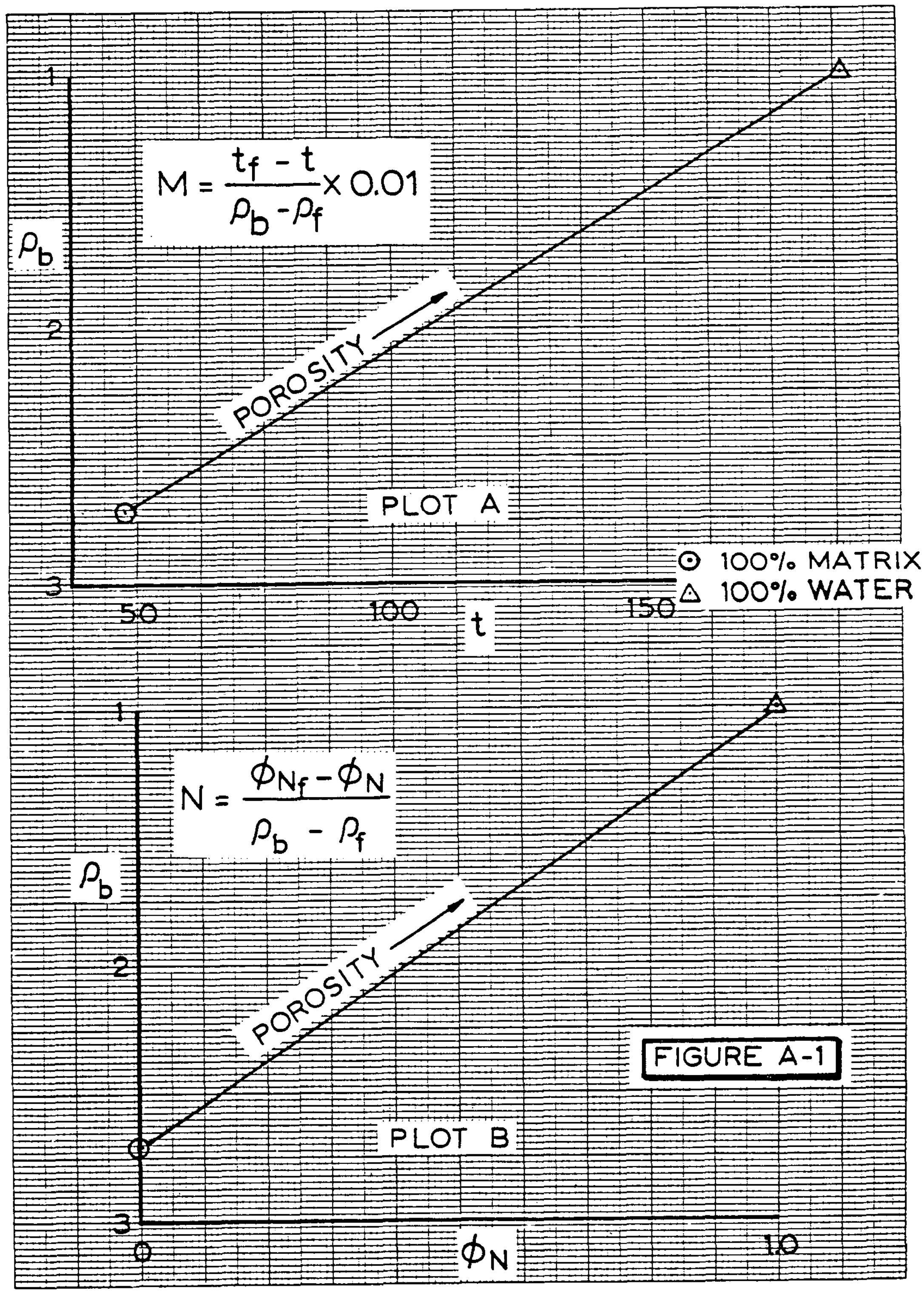

FIGURE A-1

☆ U.S. Government Printing Office: 1979 — 677-013/48

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PRESENTS

RESULTS FROM

LOGCALC

This computation based on: 2 - MINERAL Model.

Presentation made for: L. A. S. L.

FIGURE 4.16

WELL DATA

COMPANY: L. A. S. L.

WELL: FENTON HILL GT-2

FIELD: FENTON HILL

COUNTY: SANDOVAL STATE: NEW MEXICO

DATE 08/01/78	LOCATION	ELEVATION 8702.4 KB
		DF
RUN NO. [illegible]	SEC. 13 TWP. 19N RGE. 2E	[illegible] GL

LOG TRACES USED IN PRESENTATION

Trace Name	Date Logged	Run No.	Service Company
GAMMA RAY	05/14/74	1	SCHLUMBERGER
CALIPER	05/14/74	1	SCHLUMBERGER
BULK DENSITY	05/14/74	1	SCHLUMBERGER
COMPENSATED NEUTRON	05/14/74	1	SCHLUMBERGER
INTERVAL TRANSIT TIME	05/14/74	1	SCHLUMBERGER
DEEP INDUCTION	05/14/74	1	SCHLUMBERGER
LATEROLOG-8	05/14/74	1	SCHLUMBERGER

Traces Digitized by: SCIENTIFIC SOFTWARE CORPORATION

Project No.: 232900 Well No. 29002

COMPUTATION PARAMETERS

Depth Interval		Resistivity			Density		Acoustic			Neutron	
From	To	R_w	R_{mf}	R_z	ρ_{ma}	ρ_f	Δt_{ma}	Δt_f	C_p	Matrix	Hole Fluid
6250	6650										

a = m =

Remarks:

RHOGA = APPARENT GRAIN (MATRIX) DENSITY

DIFCAL = CALIPER - BITSIZE

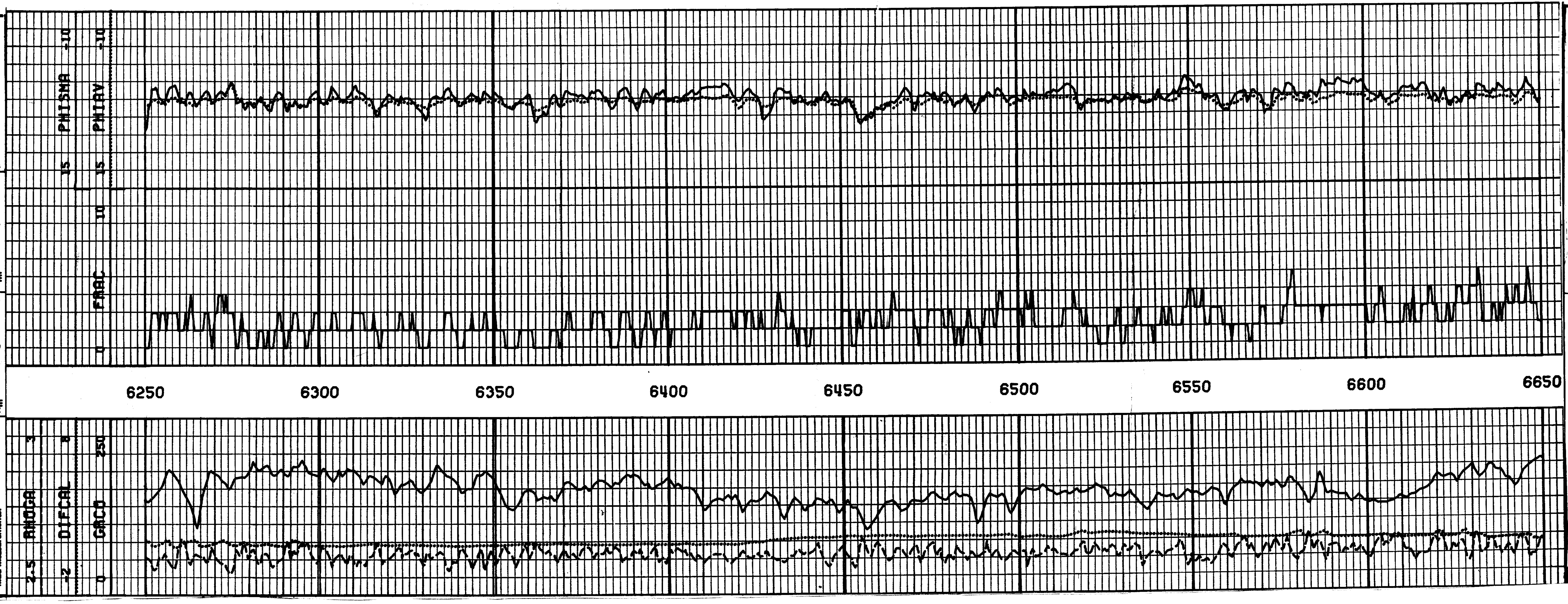
GRCO = GAMMA RAY CORRECTED FOR HOLE SIZE AND MUD WEIGHT

FRAC = INDEX WHICH INCREASES WITH LIKELIHOOD OF FRACTURING

PHISMA = SONIC POROSITY, MATRIX ADJUSTED

PHIAV = AVERAGE POROSITY FROM DENSITY-NEUTRON 2-MINERAL MODEL

Mud Measurements: R_m = @ °F R_{mf} = @ °F BHT = °F



WELL DATA

COMPANY: L. A. S. L.

WELL: FENTON HILL GT-2

FIELD: FENTON HILL

COUNTY: SANDOVAL STATE: NEW MEXICO

SCIENTIFIC SOFTWARE CORPORATION

SCIENTIFIC SOFTWARE CORPORATION

PRESENTS

RESULTS FROM

LOGCALC

This computation based on: BASE DATA Model.

Presentation made for: L. A. S. L.

WELL DATA

FIGURE 4.17

COMPANY: SEE TEXT

WELL: RAGE NO. 2

FIELD: RAFT RIVER GEOTHERMAL

COUNTY: CASSIA STATE: IDAHO

DATE 08/01/78 LOCATION NE-NE

RUN NO. ONE SEC. 23 TWP. 15S RGE. 26E

ELEVATION [illegible] KB, DF, [illegible] GL

LOG TRACES USED IN PRESENTATION

Trace Name	Date Logged	Run No.	Service Company
BULK DENSITY	08/27/75	2	SCHLUMBERGER
COMPENSATED NEUTRON	08/27/75	2	SCHLUMBERGER
INTERVAL TRANSIT TIME	08/27/75	2	SCHLUMBERGER
GAMMA RAY	08/27/75	2	SCHLUMBERGER
CALIPER	08/27/75	2	SCHLUMBERGER

Traces Digitized by: SCIENTIFIC SOFTWARE CORPORATION

Project No.: 232800 Well No.: 2800W

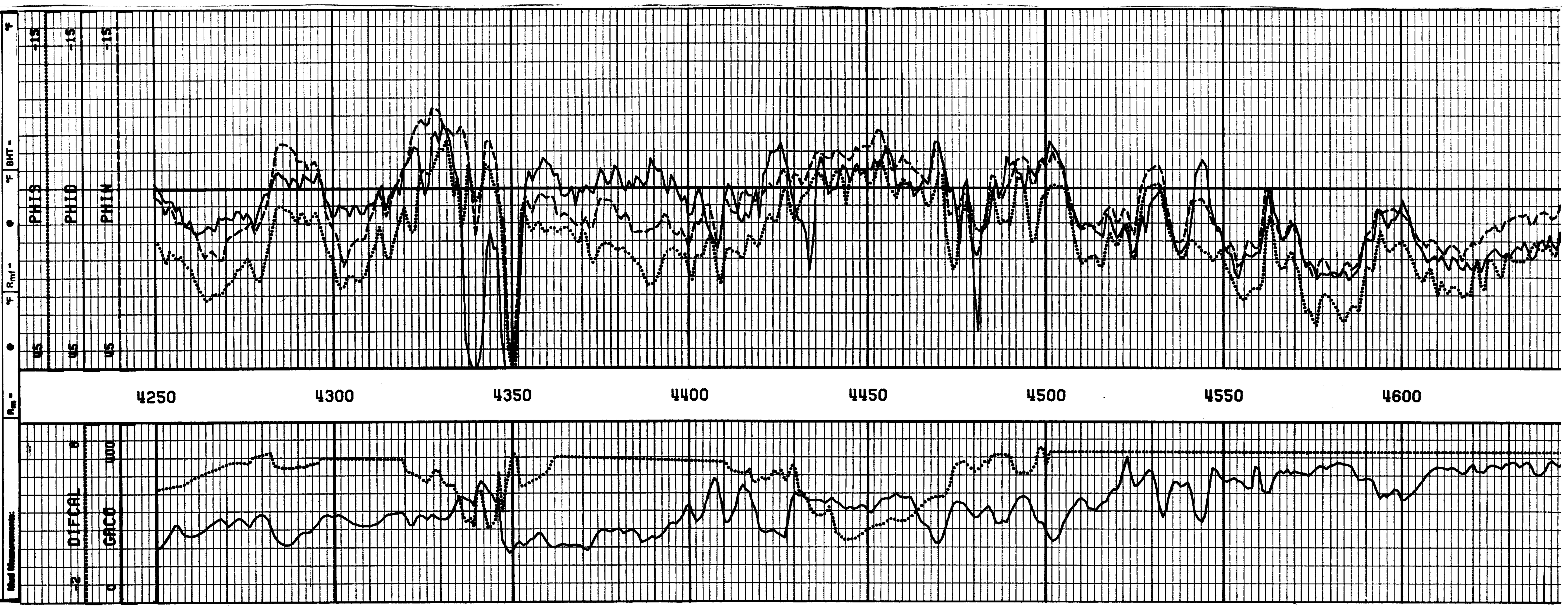
COMPUTATION PARAMETERS

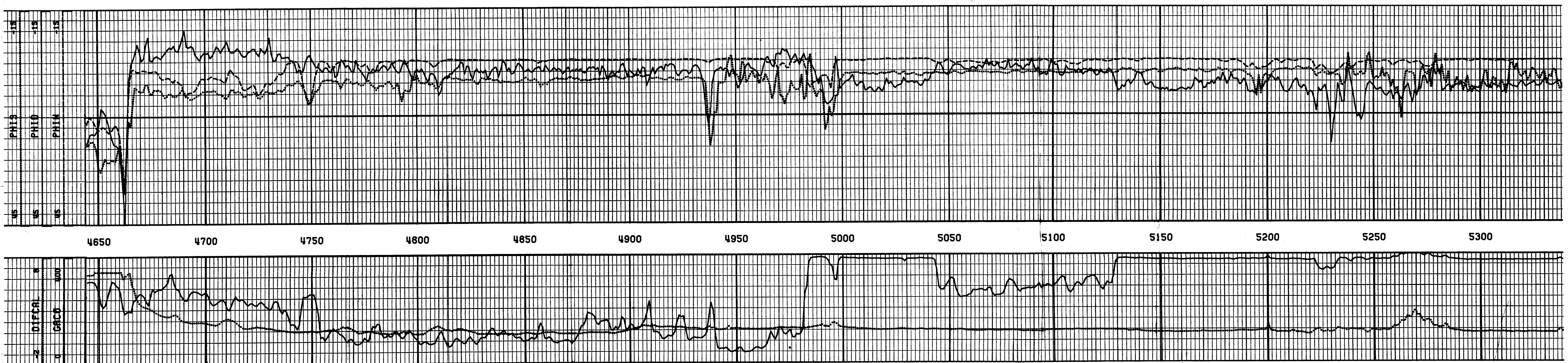
Depth Interval		Resistivity			Density		Acoustic			Neutron	
From	To	R_w	R_{mf}	R_z	ρ_{ma}	ρ_f	Δt_{ma}	Δt_f	c_p	Matrix	Hole Fluid
4250	5980										

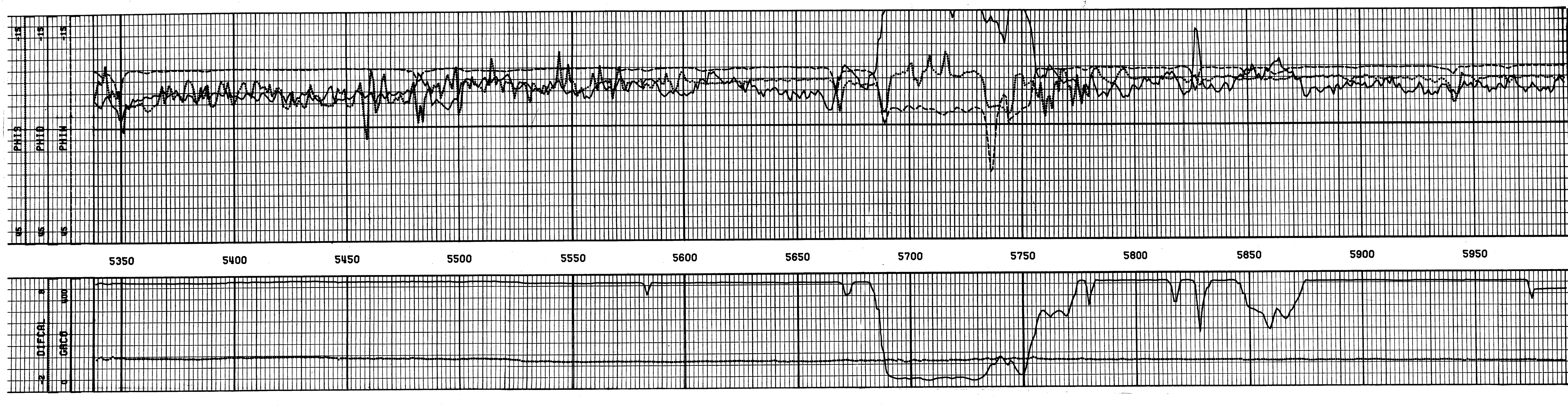
a = m =

Remarks:
DIFCAL = CALIPER - BITSIZE
GACO = GAMMA RAY CORRECTED FOR HOLE SIZE AND MUD WEIGHT
PHIS = SONIC POROSITY -LIMESTONE UNITS
PHID = DENSITY POROSITY -LIMESTONE UNITS
PHIN = NEUTRON POROSITY -LIMESTONE UNITS

Mud Measurements: R_m = @ °F R_{mf} = @ °F BHT = °F







WELL DATA

COMPANY SEE TEXT

WELL: RAGE NO. 2

FIELD: RAFT RIVER GEOTHERMAL

COUNTY: CASSIA STATE: IDAHO

SCIENTIFIC SOFTWARE CORPORATION

SCIENTIFIC SOFTWARE CORPORATION

PRESENTS

RESULTS FROM

LOGCALC

This computation based on: 3-MINERAL Model.

Presentation made for: L. A. S. L.

WELL DATA

FIGURE 4.18

COMPANY: SEE TEXT

WELL: RAGE NO. 2

FIELD: RAFT RIVER GEOTHERMAL

COUNTY: CASSIA STATE: IDAHO

DATE 08/01/79 LOCATION NE-NE

RUN NO. ONE SEC. 23 TWP. 15S RGE. 26E

ELEVATION 4863 KB, DF, 4845 GL

LOG TRACES USED IN PRESENTATION

Trace Name	Date Logged	Run No.	Service Company
BULK DENSITY	06/27/75	2	SCHLUMBERGER
COMPENSATED NEUTRON	06/27/75	2	SCHLUMBERGER
INTERVAL TRANSIT TIME	06/27/75	2	SCHLUMBERGER
GAMMA RAY	06/27/75	2	SCHLUMBERGER
CALIPER	06/27/75	2	SCHLUMBERGER

Traces Digitized by: SCIENTIFIC SOFTWARE CORPORATION

Project No.: 232900 Well No.: 29004

COMPUTATION PARAMETERS

Depth Interval From	Depth Interval To	Resistivity R_w	Resistivity R_{mf}	Resistivity R_z	Density ρ_{ma}	Density ρ_f	Acoustic Δt_{ma}	Acoustic Δt_f	Acoustic C_p	Neutron Matrix	Neutron Hole Fluid
4250	5980										

a = m =

Remarks:

DIFCAL = CALIPER - BITSIZE

RHOGA = APPARENT GRAIN (MATRIX) DENSITY

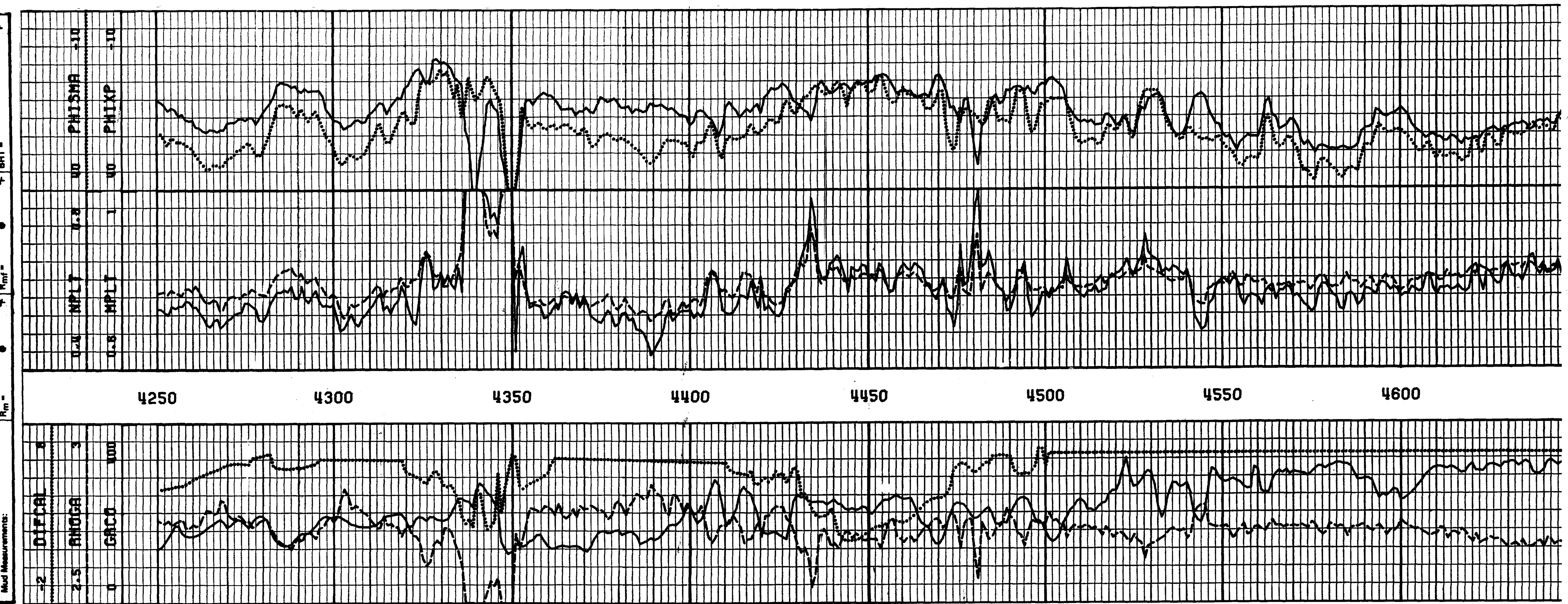
GACO = GAMMA RAY CORRECTED FOR HOLE SIZE AND MUD WEIGHT

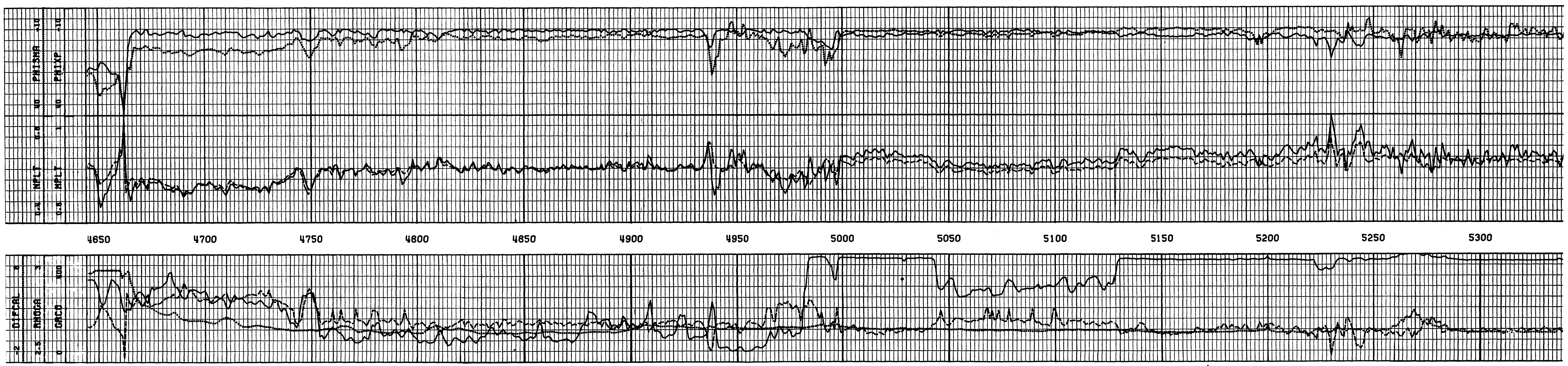
NPLT, MPLT = N AND M VALUES

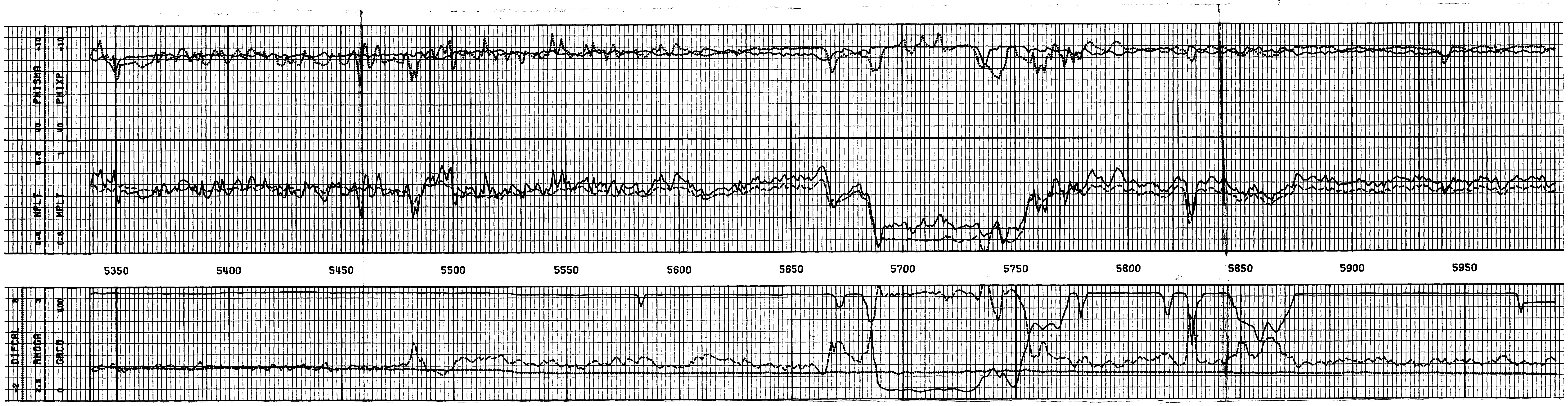
PHISMA = SONIC POROSITY, MATRIX ADJUSTED

PHIXP-CROSS PLOT POROSITY FROM DENSITY-NEUTRON 3-MINERAL MODEL

Mud Measurements: R_m = @ °F R_{mf} = @ °F BHT = °F







WELL DATA

COMPANY: SEE TEXT

WELL: RAGE NO. 2

FIELD: RAFT RIVER GEOTHERMAL

COUNTY: CASSIA STATE: IDAHO

SCIENTIFIC SOFTWARE CORPORATION