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Informal Report

Geothermal Well Log Interpretation

State of the Art

Final Report

MASTER

University of California

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Geothermal Well Log Interpretation

State of the Art

Final Report

Prepared for
Los Alamos Scientific Laboratory

by

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GEOTHERMAL WELL LOG INTERPRETATION

STATE OF THE ART

FINAL REPORT

by

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

ABSTRACT

An in-depth study of the state of the art in Geothermal Well Log Interpretation has been made encompassing case histories, technical papers, computerized literature searches, and actual processing of geothermal wells from New Mexico, Idaho, and California. A classification scheme of geothermal reservoir types was defined which distinguishes fluid phase and temperature, lithology, geologic province, pore geometry, salinity, and fluid chemistry.

Major deficiencies of Geothermal Well Log Interpretation are defined and discussed with recommendations of possible solutions or research needed for solutions.

The Geothermal Well Log Interpretation study and report has concentrated primarily on Western U. S. reservoirs. Geopressured geothermal reservoirs are not considered.

1. REVIEW OF THE STATE OF THE ART

Introduction

The exploration for and development of geothermal energy is a long, complex, and expensive process. Initial efforts for locating potential geothermal resources are primarily surface or near surface exploration techniques such as seismic, microseismic, magneto-telluric, electrical resistivity, geochemical, gravity, heat flow, and temperature gradient measurements. These methods are normally used in conjunction with comprehensive geological studies. Once a potential geothermal system is located, verification of its existence must be made by the actual drilling and testing of wells. At this point, all available data should be collected in order to answer questions such as:

- What is the origin and nature of the system?
- What is the system's heat content?
- How much heat is recoverable?
- At what rate can heat be extracted?
- What type of energy usage is envisioned?
- How long will the system last?
- How will the production decline?
- What type of surface facilities are required?
- Is the project economically viable?

Most of these questions can only be answered as accurately as the facts are known about the system under

consideration. Even the requirements for accuracy may vary from reservoir to reservoir. For instance, if power generation is desired, the question of economic viability is more critical for a given reservoir with 175°C water, than if the same reservoir contained 250°C water.

Managers, engineers, and geologists all need a cost effective system to gather as much data as accurately as possible to properly evaluate a prospect. Borehole logging and the interpretation of these measurements to estimate reservoir parameters and geological characteristics has proven to be one of the most cost effective means of providing such data. Even though borehole logging cannot answer all questions, it is one technique which makes measurements in situ, resulting in the most accurate method for determining depth, thickness, and other reservoir parameters. Flow testing of wells may also provide in situ reservoir parameters such as permeability and porosity. However, these calculated parameters are average values for the drainage volume of the well, whereas well logging can provide meter-by-meter definition of reservoir properties in the immediate vicinity of the borehole.

It may be possible to develop and produce a geothermal system without any, or with very little, information from well logs. However, experiences in the petroleum and mineral industries show that sparse initial information may result in surface equipment (gathering systems, processing plants, etc.) improperly sized for the actual production, and contracts which are difficult or impossible to fulfill. The operator may then find himself in a situation in which the problem cannot be corrected in an organized and economical fashion, if at all.

Other producing operations have performed satisfactorily for a period of time and then suddenly have become plagued with downhole mechanical problems or unexplainable drops in production. Evaluating the reservoir at this time may be difficult because of the mechanical condition of the wells, and will likely be very expensive because it shuts down already sagging production.

In Tulsa, Oklahoma on June 8, 1979, the Geothermal Log Interpretation Steering Committee of the U.S. Department of Energy (sponsored by Los Alamos Scientific Laboratories (LASL), Mark Mathews-Program Manager) met for a review of the past six months' progress and to recommend the direction for future effort. The Well Log Analysts Subgroup was composed of representatives from industry, service companies, universities, consultants, and government. This group developed the following list of priorities for needed development of log measurements and interpretation techniques.

- A. Formation evaluation: Those measurements made in the borehole ultimately to be used to characterize the entire reservoir.
 - 1. True formation temperature profiles by time-lapse temperature measurements,
 - 2. Lithology, depth, and thickness of formations,
 - 3. Intergranular and fracture permeability,
 - 4. Intergranular and fracture porosity,
 - 5. Further characterization of fracture systems,
 - 6. Borehole geometry,
 - 7. Fluid composition,
 - 8. Thermal conductivity and heat capacity,
 - 9. Elastic moduli of rock.

B. Production management: Those measurements in or near the wellbore required in an engineering sense to keep the well producing over a number of years and to provide data for design and operation of surface facilities.

1. Flow profile including flow rate,
2. Pressure profile,
3. Fluid composition,
4. Hole and/or casing mechanical conditions such as:
 - a. scaling;
 - b. corrosion;
 - c. cement quality;
 - d. mechanical properties of the borehole system itself.

The midterm report of this Geothermal Well Log Interpretation Study (LA-7693-MS, February, 1979) listed four items that were among the first five items prioritized by the Steering Committee. This final report looks further into these areas to evaluate the state of the art and determine what improvements need to be made to refine and increase the information obtainable from borehole geophysical logging.

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 undertaking.

By and large, 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 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 150°C or 300°F) than those in petroleum wells. In many geothermal wells, some of the standard well logs cannot be run because the well temperatures are higher than the maximum temperature for which the logging tools are designed.

Logging service companies are developing 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 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, development in both instrumentation and interpretation by the logging industry has been inadequate to fulfill 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 program of tool development for geothermal logging. These programs have progressed well and there are indications that many 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 well logging. These problems (Sanyal and Meidav, 1977) are in the areas of logging objectives, operation, and interpretation.

Logging Objectives

The most important objectives of petroleum well logging are the determination of porosity and of 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. However, geothermal reservoirs have negligible hydrocarbon saturation and the nature of their porosity is usually substantially different from that in petroleum reservoirs. The majority of geothermal reservoirs have fracture porosity while the vast majority of petroleum reservoirs have intergranular porosity. The state of the art of detection and quantification of the characteristics of fractures is relatively undeveloped in the logging industry. It is 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 between the objectives of the two logging industries are caused by differences in the types of reservoir. Petroleum reservoirs have mostly intergranular porosity and occur in relatively soft, sedimentary rocks at temperatures less than 150°C

(300°F) with water saturation less than 100%. Geothermal reservoirs usually have fracture porosity and occur in hard, igneous and metamorphic rocks at temperatures higher than 150°C (300°F) and with almost 100% water (and rarely, steam or free gas) saturation.

Assessments of reservoir lithology and permeability are common to both industries. Here again basic differences occur. The majority of 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 to 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 Operations

Routine well logging instrumentation used in the petroleum industry is capable of working up to 177°C (350°F) temperature. However, the majority of geothermal

reservoirs are at higher temperatures. Sometimes the well bore can be cooled to 177°C (350°F) or lower by circulation of cooled fluids before logging; however, this consumes precious rig time, can be hazardous for open holes, and may also affect the well log measurements. In the case of the dry steam reservoirs at The Geysers (California), lost circulation problems are severe and wells here are usually drilled with air, so cooling the borehole by fluid circulation is impractical. Many reservoirs are simply too hot to be cooled 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 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 up to temperatures of 260°C (500°F) (Ehring and others, 1978). Sandia Laboratories have 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 Televier 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. This may cause operational problems such as a stuck tool or poor log quality.

Since geothermal logging is only a few years old, very few logging field engineers have substantial experience in geothermal logging. This lack of experience may cause some problems during logging and recording to 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. Some geothermal logs may be of poor quality due to high logging speed, improper scaling or calibration, unusual cable stretching, rugosity of the borehole, temperature effect, etc. Typical examples of such problems are:

- Discrepancies in depth between logs from the same well,
- Lack of repeatability,
- Improper scale,
- Unusually high apparent porosity because of borehole rugosity,
- Unusually high or low porosity due to wrong assumption of lithology,
- Featureless, wandering SP curve (due to stray currents) through a thick, tight section,

- SP baseline shift,
- Mutually inconsistent responses of logs in a suite,
- Inconsistency in water resistivity calculated by different methods, and
- Inconsistent or incomplete job-specific data.

Most of the above-mentioned problems are known in the petroleum industry and some can be resolved. However, there are other types of problems associated with log interpretation that cannot be easily resolved. These are: accurate records of times at which drilling stopped; time at which circulation stopped; and times that various logging tools reached the bottom, 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 and the corresponding temperature effect on log response. These data, however, are easy to obtain if the effort is made to properly document the events.

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

For example, in LASL's Hot Dry Rock Project Well No. 2 in the Jemez Mountains, some zones show increases in bulk density without corresponding decreases in the acoustic travel time. This can be explained by the fact that the mafic rocks encountered in these zones have higher electron densities than the medium used to calibrate

the density logging tool (West and others, 1975). In the same well, a zone shows a decrease in acoustic travel time corresponding to an increase in bulk density, but the apparent neutron log porosity seems to increase. 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 (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 that of 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. The lack of calibration data for such lithologies presents a problem in interpretation. Standard interpretation charts are often inadequate for geothermal reservoir lithology, which is often complicated by hydrothermal alteration or metamorphism.

The 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 both 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 in a fractured volcanic geothermal reservoir. Some of the overlay and crossplot concepts do not apply well to 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 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 where sufficient core data are available, it is often difficult to develop a useful porosity-permeability transform from the core data. This may be due to the presence of fractures or to abrupt changes in lithology or to both.

Another problem to be considered 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 rock properties is primitive. For this reason, use of core data to normalize well log data may not be justifiable in many geothermal fields. There is a great need for research in this area.

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. 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 from the petroleum and 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 U.S. geothermal reservoirs.

Hobson and others (1966) described the logging program carried out in a slim hole 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.

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. The character of tuff varies 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.

Khatchikian and Lesta 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 in the paper 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; however, the natural radioactivity of some tuffites and the occurrence of streaming potential make it difficult to use the gamma ray and SP as clay indicators.
- (3) On the density-sonic crossplot, 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 that lie above the silica point (average values are: $M = 0.95$, and $N = 0.64$).
 - (b) Heavy tuffites that lie near the dolomite point (average values are: $M = 0.78$ and $N = 0.55$).

* 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 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 Lesta (1973).

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, magnetic permeability, and vertical magnetic field intensity. All the penetrated formations were basalt, with generally high porosities, ranging from a few percent to near fifty percent. Grain densities of the encountered rocks were about 3.02 g/cm³. The acoustic log indicated wave speeds for rocks with no porosity of approximately 5 730 m/s (18 800 ft/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 10¹⁴ Pa. While the neutron-density crossplot was linear, the neutron-sonic crossplot was not, indicating that the time-average formula for sonic log response was not accurate for this lithology. Based on measurements made on 400 core plugs of the basalt from the well, the following empirical relation was obtained:

$$F = 18\phi^{-1.05} \quad (1.1)$$

where F is the formation resistivity factor
and ϕ 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 Geothermal Energy Development Program. 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 estimated to be 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 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. A spectral gamma ray log was very useful in distinguishing some lithologies. A full-waveform sonic log was very useful in locating fractures and a borehole seismviewer log was quite effective in delineating fractures.

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 4 300 m (15 750 ft). The four lithologies encountered were:

- (1) Quartzite - metamorphosed sandstone,
- (2) Phyllite - metamorphosed derivative of fine-grained sediment,
- (3) Calcite marble - metamorphosed limestone, and
- (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 questionable for quantitative use. The bulk densities and the interval transit times measured were higher than the grain densities and matrix 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 in which the 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 on the neutron log of structural (bound) water present in the rock. 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 andesite-latite. Both examples are from low-porosity rocks where the effect of 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 they 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.

West and Laughlin (1976) discussed the utility of spectral gamma ray logging in the first two wells of the LASL Hot Dry Rock Program. These authors reported that

spectral gamma ray logging was useful for determining rock types, detecting fracture zones, and studying mobility of the elements U, Th, and K.

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 the borehole televiwer for locating and evaluating fractures. Examples were shown from the Long Valley (California) and Fenton Hill (New Mexico) geothermal areas. He presented a neutron-density crossplot from the Raft River (Idaho) geothermal field.

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.

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 log interpretation program for steam wells that calculates lithology, porosity, steam entry zones, and steam quality. They pointed out that more research and field experience will be necessary before their work is completed.

Keys (1979) presented several examples of well log interpretations in igneous and metamorphic rocks. He pointed out that core analysis data plotted against log

response and the crossplotting of various logging variables were particularly useful for identifying the various rock types in an igneous complex. He showed that for the cases he presented, hydrothermal alteration could be recognized on well logs through the use of crossplots and spectral gamma ray logs. He presented a number of examples of the use of the acoustic televiewer and multiaxis acoustic calipers supported by other logs in detecting fractures.

Glen and Hulen (1979) analyzed well logs from four wells in the Roosevelt Hot Springs KGRA in Utah. They pointed out the significant effects of water in hydrated minerals on the neutron log and that of denser, metallic minerals on the density log. They showed that mineralogic variations could have a greater effect on the neutron and density logs than does very low porosity. For example, they pointed out that water in hydrated minerals could produce a neutron response equivalent to three percent porosity. Heavy mineral variations can produce an even larger apparent porosity variation if porosity is computed from the density log using a uniform value of matrix density.

Ershaghi and others (1979) used standard oil field techniques to analyze logs from four geothermal wells in a sand/shale sequence in the Cerro Prieto field in Mexico. They employed graphical and numerical trial-and-error techniques to estimate the formation water resistivity, even though some formation parameters were unknown. SP, gamma ray, dual induction-laterolog, density, and sonic logs were used in the study.

Sanyal and others (1979) applied an empirical, statistical approach to analyzing a suite of density,

neutron, acoustic, gamma ray, caliper, and temperature logs from a geothermal well in a rhyolite/basalt/volcanic ash sequence. Various histograms, crossplots, and statistical correlation parameters were used to diagnose lithology, detect permeable zones, and estimate the thickness of the producing interval. Neutron and gamma ray logs were found to be the most effective diagnostic tools to determine lithology, while a combination of caliper, porosity, and temperature logs helped detect fracture zones.

Applegate and others (1979) presented a case history of geothermal well log analysis from the Raft River geothermal field in Idaho. The authors used the crossplotting of various logging variables to diagnose the lithologic types.

Sheff and Upton (1979) presented a log evaluation from a geothermal well at Coso Hot Springs. The authors concluded that the data were inadequate for a complete analysis, but that definite signs could be found pointing to the utilization of logging as an aid to geothermal resource evaluation. Inadequacy of models of expected log behavior was also mentioned as hampering the interpretation of geothermal well logs.

Sanyal and Jusbasche (1979) presented a case history of a statistical estimate of average formation water salinity for different intervals of a geothermal well in the Raft River geothermal field. These authors used resistivities from deep induction and shallow focused devices run through a sedimentary-volcanic debris sequence.

Besides the preceding published case histories, several workers have made oral presentations of geothermal log interpretation results in technical meetings. For example, Sanyal (1976 and 1977) has discussed a number of case histories of geothermal well log analysis in oral presentations. 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 containing pyrite have been reported. Pyritization is also seen in geothermal fields. Disseminated pyrite has been found to disturb 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, at times, can be used to detect the existence of pyrite. If the porosity and nature of hydrocarbon present can be determined by other techniques, the volume of pyrite can be estimated from the density log. 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 formation, the low-frequency resistivity measurement remained essentially undisturbed. Increasing the frequency appeared to lower the measured value of resistivity in a manner 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. Some recommendations were given concerning the logging program for formations containing pyrite.

As part of a continuing laboratory study, Keller (1977) reported that the formation resistivity factor of volcanic rocks was consistently higher than would be indicated by Archie's formula for the same porosity. He 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). He 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 strain. 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 the 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 the 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. According to the authors, minor discrepancies could be explained, as proposed by Simmons and Nur (1968). Significant discrepancies were encountered by Roegiers and Thill (1976) in determining porosity in the laboratory and from logs. They concluded that estimation of porosity from either sonic or neutron logs 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 1.1032×10^8 Pa (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 an increase in pressure and with liquid saturation. If the effects of temperature and pressure on sonic velocities are ignored, then errors in the estimation 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 effective 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 geothermal well logs must take into account the effects of temperature on rock properties and the differences between the petrophysical properties of geothermal reservoir rocks and the sedimentary rocks that comprise petroleum reservoirs.

Table 1.1 summarizes the current utility of the commonly available well logs for geothermal reservoirs in 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 multi-log analysis and various computer techniques, which can have significant synergistic effect on geothermal formation evaluation. The only

TABLE 1.1
UTILITY OF VARIOUS WELL LOGS IN NON-SEDIMENTARY LITHOLOGY
 (From Sanyal and Meidav, 1977)

<u>LOG TYPE</u>	<u>COMMENTS</u>
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.

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, more field experience will be necessary before any interpretation technique 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. Interpretation examples from three areas are given in this report under Section 4.

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

The interpretation of temperature logs and the 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 in this area is presented in Section 5.d of this report.

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2. CLASSIFICATION OF GEOTHERMAL RESERVOIR TYPES

Introduction and Rationale

This section defines geothermal reservoirs from the viewpoint of well log analysis with the expectation 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 a classification scheme is to examine the important reservoir characteristics which have a bearing on log response.

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

- Lithology,
- Fluid Phase,
- Fluid Chemistry,
- Reservoir Temperature,
- Pore Geometry, and
- Certain Overall Geological Factors.

Lithology is perhaps the most important reservoir property that affects log response because rock matrix occupies the major fraction of the bulk volume of a formation. Fluid phase is important because water and steam in geothermal reservoirs 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 either a liquid or a vapor phase). The chemistry of geothermal waters varies extensively depending on the nature and quantity of dissolved solids and gases, far more so than do oilfield waters. The amount of total dissolved solids (TDS), expressed as "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 because 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 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., with regard to 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 the above discussions, it seems logical that as regards well log analysis, geothermal reservoirs can be classified 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 the 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" and 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 (LASL).

TABLE 2.1
GEOTHERMAL RESERVOIR CLASSIFICATION SCHEMES

- I. According to Fluid Phase & Temperature:
 - A. Steam
 - B. High Temperature Water: $> 204^{\circ}\text{C}$ (400°F)
 - C. Moderate Temperature Water: $149\text{--}204^{\circ}\text{C}$ ($300\text{--}400^{\circ}\text{F}$)
 - D. Low Temperature Water: $< 149^{\circ}\text{C}$ (300°F)
 - E. Dry
- II. According to Lithologic Type:
 - A. Sedimentary Clastic
 - B. Sedimentary Carbonate
 - C. Metamorphic
 - D. Igneous (crystalline & glassy)
 - E. Volcanic Ash and associated sediments
 - F. Breccia/Conglomerate
- 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
 - D. Vuggy
- 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. Hypersaline: $> 100\ 000$ ppm
 - E. Dry

The temperature in a hot water reservoir may range anywhere from ambient temperature 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 149°C (300°F), which is generally 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 fluid, the higher is the thermodynamic efficiency of energy conversion and the better are 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 grouped into the following temperature classes: high -- greater than 204°C (400°F); Moderate -- between 149°C (300°F) to 204°C (400°F); or Low -- less than 149°C (300°F).

Figure 2.1 presents the temperature distribution of the known hot water reservoirs in the U.S., derived from the data reported in Circular 790 of the U.S. Geological Survey (1978). Figure 2.1 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 217 hot water

Fig. 2.1. Temperature distribution of known hot water reservoirs in the U.S.

reservoirs listed in Circular 790 of the U.S.G.S., 164 belong to low temperature class, 37 to the moderate and 16 to the high. Figure 2.1 also 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 moderate class. However, the low temperature class, since it is 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.

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%. Although rare in occurrence, the dry steam reservoirs are prolific sources of power. Only two other 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 of 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 m (600 to 9 000 ft). Below about 300 m (1 000 ft), 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 they are 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, D.C. 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 a 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 California. This is a deterrent to running well logs which require a radioactive source.

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 moderate temperature class if the well can be cooled by circulation to below 177°C (350°F), which is the current practical limit of effective operation for most logging devices. It may be impractical to cool many of the high temperature class wells sufficiently for logging with the standard tools. High temperature logging tools and cables have recently been developed that 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 will still persist.

Suites of logs including temperature, resistivity, SP, neutron, density, gamma ray, and caliper have been run in many hot water wells. Dipmeter, acoustic velocity, borehole televiewer, spectral gamma ray, 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 increasing temperature (Weinbrandt (1972), Casse (1974), Aruna (1976), etc.). For this reason, the practice of normalizing 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, 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 intrusive 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 sometimes exhibit 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 normally calibrated and tested against known lithologies common in 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, but for many unfamiliar lithologies, such corrections cannot be estimated. For example, in the Hot Dry Rock Program 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 both a high neutron capture cross section 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. During logging in an unfamiliar lithology and in subsequent analysis of logs, some log quality problems may remain undetected. Matrix properties (such as bulk density, sonic travel time, matrix neutron porosity, or neutron capture cross section) of igneous and metamorphic rocks have been unavailable in the logging literature. Matrix properties have been available for only a few of the minerals that form igneous and metamorphic rocks. Section 5.b of this report deals with the problem of matrix properties.

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. Non-marine 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); sand-silt-shale sequence interlayered

with volcanic ash, tuff, and volcanic flow (for example, Raft River, Idaho); or rarely, of carbonate lithology. 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, fracturing, unusual chemistry of reservoir water, 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 systematic log analysis techniques will evolve for these lithologic types. The conventional complex lithology analysis aided by crossplots, histograms, and computer processing can be applied to igneous and metamorphic-type lithologies. However, 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 beginning to evolve in the geothermal industry. For

example, the log analysis for the Imperial Valley, California geological province is standardized for all practical purposes -- sand-shale analysis techniques based on induction (or dual induction -- shallow focused device combination) and the three porosity log suite. Log analysis procedures for most 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 an 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. 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. Although the northern Gulf of Mexico Basin contains "geopressured" geothermal reservoirs, that geologic province is not within the scope of this study and has been excluded from this classification.

Basin and Range Province

This geological province covers most of Nevada, as well as parts of Utah, Oregon, California, Idaho, and Arizona. Two major belts of geothermal resource sites

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Fig. 2.2. Geothermal Exploration and Development in the Western United States 1968-1975.

stretch along the eastern and western margins of the Basin and Range province. The eastern belt covers the Wasatch Front and the area just east of it and includes 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 of these geothermal reservoirs (such as Roosevelt Hot Springs) have higher temperatures. Exploratory drilling at Roosevelt Hot Springs indicates a high temperature hot-water reservoir that is of sufficient quality and quantity for commercial 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 km. It has a maximum width

of 130 km in the vicinity of Reno, Nevada, where it extends eastward across the Carson Desert. Several hot water geothermal reservoirs have been identified in this belt.

Information available on 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 those of coping with unfamiliar lithologies (intrusive and extrusive volcanics) and hydrothermal alterations, and the detection of fracture zones.

Northwest Province

This province covers major portions 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 southern Idaho and eastern Oregon; it 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 temperatures. Most of the reservoirs in the Snake River Plain are of the Low Temperature Water 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 2 to 10 million year-old basaltic

and andesitic lavas and many recently active volcanoes, such as Hood, Shasta, Lassen, Baker, Three Sisters, and St. Helena. Occasional fumaroles are present, such as in 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 temperature 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.

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, log 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. This makes fracture detection from well logs 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 MW geothermal power plant has been in operation since 1973 and a second 75 MW plant is under construction. According to our classification scheme, this is a High Temperature and Moderate Salinity 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 associated 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 a 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 formation 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. 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 Geysers' reservoirs are intensely faulted and fractured graywacke. This is a subhydrostatic, dry-steam field. Low temperature water reservoirs have been utilized in some 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 Water reservoir (of fractured

tuff) is being developed for electrical power generation. Close to that field, LASL is experimenting with energy extraction from hot dry rocks. The main logging problems are those of deciphering unfamiliar lithology and of fracture detection. Further north into Colorado, the town of Pagosa Springs is further developing applications of hot water for heating. In the San Luis Valley, Colorado, greenhouses and a fish farm utilize low temperature water commercially. Very little wireline logging has been performed in geothermal wells of this region.

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 1μ radius or a single fracture of 0.0314μ 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 common, followed by intergranular, vesicular, and vuggy types in frequency of occurrence. The majority of the reservoirs with crystalline igneous and metamorphic rocks possess fracture permeability only. The reservoirs with sedimentary lithology usually possess intergranular permeability and fracture permeability may develop if the sediments are well consolidated, hydrothermally altered, or metamorphosed. Vesicular pore geometry is seen in some volcanic flows, particularly in basaltic flows. Usually vesicular pore geometry gives rise to high porosity, an extreme case being that of pumice, which is an extremely porous volcanic rock. Vuggy porosity is usually present in carbonate rocks. 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% 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% porosity and 200 millidarcies 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 that 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 sometimes 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 usually 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 SP 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. In fracture zones, sonic wave amplitudes may decrease sharply, the compressional wave being more affected by vertical or high-angle fractures and the shear wave 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. The borehole televiewer log or various multiaxis caliper logs are excellent tools to delineate fractures. A quantitative estimate of the fracture porosity can sometimes be obtained by comparing the porosity from a density or neutron log to that from a sonic log, as discussed earlier.

It is apparent from the above discussion that fractures can 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 to 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 of the formation 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 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.

The "sodium chloride (NaCl) equivalent," of TDS is not an adequate description of the chemistry of a geothermal fluid, because 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 whose maximum concentration is over 10 000 ppm), secondary (maximum 1 000 - 10 000 ppm), minor (maximum 1 - 1 000 ppm) and trace (less than 1 ppm) constituents of geothermal waters. Detailed chemical analyses of geothermal waters are not always available, but their TDS usually 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 the 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 the calculated cementation factor is likely to be too low. For many low salinity geothermal systems, the resistivity of the mud filtrate is close to, or even less than, that of the formation water. This causes SP deflections to become less negative or may even cause an SP to be reversed.

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 United 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-eight 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/C means both type IIA and IIC lithologies are present in the reservoir. An attempt was made to type all KGRA's 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.

Although the group of reservoirs shown in Table 2.5 is a statistically small sample (28 reservoirs as compared to 218 identified according to U.S.G.S Circular 790), 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. A few conclusions can be drawn (about reservoirs under current development) from Table 2.6:

- Hot water reservoirs are far more frequent than steam or dry reservoirs.
- Sedimentary clastic, igneous (crystalline and glassy), and volcanic ash are the most frequent reservoir lithologies.
- The Basin & Range province contains the greatest number of hydrothermal geothermal sites. This province, the Northwest Volcanic, and the Salton Trough provinces contain the bulk of the hydrothermal reservoirs.
- Fracture-type is the most common pore geometry.
- Low Salinity reservoirs are the most frequent.

Such conclusions would be more statistically significant if data were available on more KGRA's; however, these conclusions should help the industry and DOE 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, and others, 1977)

<u>Constituent</u>	<u>Concentration in ppm</u>
Aluminum (Al)	0 - 7140
Ammonium (NH ₄)	0 - 1400
Arsenic (As)	0 - 12
Barium (Ba)	0 - 250
Boron (B)	0 - 1200
(BHO ₂)	13.6 - 4800
Bromide (Br)	0.1 - 3080
Cadmium (Cd)	0 - 1
Calcium (Ca)	0 - 62900
Carbon Dioxide (CO ₂)	0 - 490
(HCO ₃)	0 - 10150
(CO ₃)	0 - 1653
(HCO ₃ + CO ₃)	20 - 1000
(CO ₂ + HCO ₃ + CO ₃)	15 - 7100
Cesium (Cs)	0.002 - 22
Chloride (Cl)	0 - 241000
Cobalt (Co)	0.014 - 0.018
Copper (Cu)	0 - 10
Fluoride (F)	0 - 35
Germanium (Ge)	0.037 - 0.068
Hydrogen Sulfide (H ₂ S, total)	0.2 - 74
Iodide (I)	0 - 105
Iron (Fe)	0 - 4200
Lanthanum (La)	20
Lead (Pb)	0 - 200
Lithium (Li)	0 - 300
Magnesium (Mg)	0 - 39200
Manganese (Mn)	0 - 2000
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 ₂ PO ₄)	0.02 - 0.22
Potassium (K)	0.6 - 29900
Rubidium (Rb)	0 - 169
Silica (SiO ₂ , total)	3 - 1441
Silver (Ag)	0 - 2

TABLE 2.2.
(cont'd)

CHEMICAL COMPOSITION OF GEOTHERMAL WATERS
(FROM TSAI, and others, 1977)

<u>Constituent</u>	<u>Concentration in ppm</u>
Sodium (Na)	2 - 79800
Strontium (Sr)	0.133 - 2000
Sulfate (SO ₄)	0 - 84000
Sulfur (S)	0 - 30
Total Dissolved Salts	47 - 387500
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), Lanthanum (La), 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, and others, 1977)

<u>Constituent</u>	<u>Concentration in volume percent</u>
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
($\text{H}_2 + \text{H}_2\text{S}$)	0.2 - 6
Mercury (Hg)	0.007 - 40.7 (ppb)
Methane (CH_4)	0 - 99.8
Nitrogen (N_2)	0 - 97.1
($\text{N}_2 + \text{Ar}$)	0.6 - 96.2
Oxygen (O_2)	0 - 64
Sulfur Dioxide (SO_2)	0 - 31

TABLE 2.4
CHEMICAL CONSTITUENTS AND RELATIVE
ABUNDANCE IN GEOTHERMAL WATERS
(from TSAI, and others, 1977)

Major Constituents
(Maximum > 10 000 ppm)

Total Dissolved			
Salts	47 - 378500	Calcium	0 - 62900
Chloride	0 - 241000	Magnesium	0 - 39200
Sulfate	0 - 84000	Potassium	.6 - 29800
Sodium	2 - 79800	Bicarbonate	0 - 10150

Secondary Constituents
(Maximum 1 000 - 10 000 ppm)

Aluminum	0 - 7140	Strontium	.133 - 2000
Carbon Dioxide (Total)	15 - 7100	Carbonate	0 - 1653
Boron Hydroxide	13.6 - 4000	Silica (total)	3 - 1441
Bromide	.1 - 3080	Ammonium	0 - 1200
Manganese	0 - 2000	Boron	0 - 1200
		Carbonate (total)	20 - 1000

Minor Constituents
(Maximum 1 - 1 000 ppm)

Zinc	.004 - 970	Zirconium	24
Carbon Dioxide	0 - 490	Cesium	.002 - 22
Lithium	0 - 300	Lanthanum	20
Barium	0 - 250	Arsenic	0 - 12
Lead	0 - 200	Copper	0 - 10
Rubidium	0 - 169	Mercury	0 - 10
Iodide	0 - 105	Oxygen	0 - 10
Hydrogen Sulfide (total)	0 - 105	Phosphate (total)	.77 - 2.57
Fluoride	0 - 35	Nickel	.005 - 2
Nitrate	0 - 35	Silver	0 - 2
Sulfur	0 - 30	Cadmium	0 - 1
		Nitrate	0 - 1

TABLE 2.4
(cont'd)

CHEMICAL CONSTITUENTS AND RELATIVE
ABUNDANCE IN GEOTHERMAL WATERS
(from TSAI, and others, 1977)

Trace Constituents
(Maximum < 1 ppm)

Antimony
Beryllium
Bismuth
Cerium
Cobalt
Dysprosium
Erbium
Europium
Gadolinium
Gallium
Germanium
Gold
Hafnium
Holmium

Indium
Iridium
Lutetium
Molybdenum
Neodymium
Niobium
Osmium
Palladium
Platinum
Praseodymium
Rhenium
Rhodium
Ruthenium
Samarium

Scandium
Selenium
Tantalum
Tellurium
Terbium
Thallium
Thorium
Thulium
Titanium
Tungsten
Uranium
Vanadium
Ytterbium
Yttrium

TABLE 2.5

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

<u>RESERVOIR</u>	<u>LOCATION</u>	<u>TYPE</u>
Beowawe	Lander/Eureka Co., Nevada	IB, IID/E, IIIAb, IVB, VA
Brady's Hot Springs	Lyon/Churchill Co., Nebraska	IB, IIA/D/E, IIIAc, IVA/B, VA
Brawley	Imperial Co., California	IB, IIA, IIIC, IVA, VC
Brigham City	Utah	ID
Bruneau-GrandView	Owyhee Co., Idaho	ID, IIA/D/E, IIIBa, IVA/C, VA
Cerro Prieto	Baja California, Mexico	IB, IIA, IIIC, IVA, VB
Chandler	Maricopa Co., Arizona	IC, VC
Clear Lake	Lake County, California	IC, IIC, IIID, IVB, VA
Coso Hot Springs	Inyo Co., California	IC, IIC/D, IIIAc, IVB, VB
Dunes	Imperial Co., California	ID, IIA, IIIC, IVA, VB
East Mesa	Imperial Co., California	IC, IIA, IIIC, IVA, VB
Fenton Hill	Sandoval Co., New Mexico	IE, IID, IIIE, IVB, VE
Fly Ranch	Nevada	ID
The Geysers	Sonoma Co., California	IA, IIC, IIID, IVB, VA
Heber	Imperial Co., California	IC, IIA, IIIC, IVA, 5B
Kelley Hot Springs	Modoc Co., California	ID, IIA/D/E/F, IIBb, IVA/B, VA
Kilanea	Hawaii Island, Hawaii	IB, IID, IIIF, IVB/C, VA
Klamath Falls	Klamath Co., Oregon	ID, IIA/E, IIBb, IVA/B/C, VA

TABLE 2.5
(cont'd)

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

<u>RESERVOIR</u>	<u>LOCATION</u>	<u>TYPE</u>
Long Valley	Mono Co., California	IC,IID/E,IIIAc,IVB,VA
Mountain Home	Elmore Co., Idaho	IC,IID/E,IIIBa,IVB/C,VA
Raft River	Cassia Co., Idaho	ID,IIA/D/E,IIIBa,IVA,VA
Roosevelt Hot Springs	Beaver Co., Utah	IB,IID,IIIAa,IVB,VB
Salton Sea	Imperial Co., California	IB,IIA/C/D,IIIC/IVA/B,VD
Steamboat Springs	Washoe Co., Nevada	IC,IID/E,IIIAc,IVB/C,VA
Surprise Valley	Modoc Co., California	IC,IIA/D/E,IIAc/Pb,IVA/B,VA
Susanville	Lassen Co., California	ID,IIA/D,IIIAc,IVA/B/C,VA
Valles Caldera	Sandoval Co., New Mexico	IB,IID/E,IIIE,IVB,VB
Yellowstone	Park Co., Wyoming	IA/B,IID/E,IIIBa,IVB/C,VA

TABLE 2.6
DISTRIBUTION OF GEOTHERMAL RESERVOIRS

<u>Type</u>	<u>Description</u>	<u>Frequency of Occurrence</u>
<u>According to Fluid Phase & Temperature</u>		
IA	Steam	7.1%
IB	High Temperature Water: > 204°C (400°F)	28.6%
IC	Moderate Temperature Water: 149-204°C (300-400°F)	32.1%
ID	Low Temperature Water: < 149°C (300°F)	28.6%
IE	Dry	3.6%
<u>According to Lithologic Types</u>		
IIA	Sedimentary Clastic	27.3%
IIB	Sedimentary Carbonate	----
IIIC	Metamorphic	9.1%
IID	Igneous (Crystalline & Glassy)	38.6%
IIE	Volcanic Ash and Associated Sediments	22.7%
IIF	Breccia/Conglomerate	2.3%
<u>According to Geologic Province</u>		
IIIA	Basin & Range	32.0%
IIIB	Northwest Volcanic	24.0%
IIIC	Salton Trough	24.0%
IIID	Northern California Coast Range	8.0%
IIIE	Rio Grand Rift & Colorado Plateau Borderland	8.0%
IIIF	Hawaii	4.0%
IIIG	Alaska	----

TABLE 2.6
(cont'd)

DISTRIBUTION OF GEOTHERMAL RESERVOIRS

<u>Type</u>	<u>Description</u>	<u>Frequency of Occurrence</u>
<u>According to Pore Geometry</u>		
IVA	Sedimentary Intergranular	31.3%
IVB	Fracture	50.0%
IVC	Vesicular	18.7%
IVD	Vuggy	----
<u>According to Salinity</u>		
VA	Low Salinity: < 5 000 ppm	56.0%
VB	Moderate Salinity: 5 000-35 000 ppm	28.0%
VC	High Salinity: 35 000-100 000 ppm	8.0%
VD	Hyper Saline: > 100 000 ppm	4.0%
VE	Dry	----

REFERENCES

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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.

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
washouts 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) logs
8. Acoustic wave recordings

Fields with the most complete data available for study are from:

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

Abbreviations used in catalog listing are as follows:

B	Birdwell,
D.A.	Dresser Atlas,
G.O.	Gearhart-Owen,
McC.	McCullough, and
S.W.S.	Schlumberger Well Services.

GEOTHERMAL WELL LOG CATALOG						PAGE 1 OF 3	
COMPANY LOS ALAMOS SCIENTIFIC LABORATORY							
WELL GT #2						FIELD FENTON HILL	
COUNTY SANDOVAL			STATE NEW MEXICO			CLASSIFICATION IE, IID, IIIE, IVB, VE	
DATE	TYPE LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING		
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		
6/4/74	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		
6/6/74	DENSITY	2	B	4272	2510		

GEO THERMAL WELL LOG CATALOG						PAGE 2 OF 3	
COMPANY						LOS ALAMOS SCIENTIFIC LABORATORY	
WELL						FIELD	
GT #2						FENTON HILL	
COUNTY						STATE	
SANDOVAL						NEW MEXICO	
						CLASSIFICATION	
						IE, IID, IIE, IVE, VE	
DATE	TYPE LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING		
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		
9/8/74	TEMPERATURE	2	S.W.S.	6678	0		
12/10/74	ACOUSTILOG	1	D.A.	9615	6500		

GEOTHERMAL WELL LOG CATALOG						PAGE 3 OF 3	
COMPANY LOS ALAMOS SCIENTIFIC LABORATORY							
WELL GT #2						FIELD FENTON HILL	
COUNTY SANDOVAL			STATE NEW MEXICO			CLASSIFICATION IE, IID, IIE, IVB, VE	
DATE	TYPE LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING		
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		

GEO THERMAL WELL LOG CATALOG

PAGE 1 OF 2

COMPANY

LOS ALAMOS SCIENTIFIC LABORATORY

WELL

EE #1

FIELD
FENTON HILL

COUNTY

SANDOVAL

STATE

NEW MEXICO

CLASSIFICATION

IE, IID, IIE, IVB, VE

DATE	TYPE LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING
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	4400
8/26/75	INDUCTION - ELECTRICAL	1	S.W.S.	6873	6424
9/25/75	ACOUSTILOG	2	D.A.	9558	6417

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COMPANY

LOS ALAMOS SCIENTIFIC LABORATORY

WELL

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FIELD

FENTON HILL

COUNTRY

STATE

SANDOVAT

NEW MEXICO

IE, IID, IIE, IVB, VE

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GEOHERMAL WELL LOG CATALOG

PAGE 1 OF 2

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

WELL

JEMEZ GRANITE NO. 1

FIELD

JEMEZ PLATEAU

COUNTY
SANDOVAL

STATE

NEW MEXICO

CLASSIFICATION
IE, IID, IIE, IVB, VE

DATE	TYPE LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING
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	1337
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

PAGE 2 OF 2

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

JEMEZ GRANITE NO. 1

JEMEZ GRANITE NO. 1

JEMEZ PLATEAU

STATE

SANDOVAL

NEW MEXICO

CLASSIFICATION

IE, LIC/E, LIE, LVB, VE

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SARDI OIL COMPANY

SARDI NO. 1

FIELD
CALIPATRIA

COUNTY

STATE
CALIFORNIA

CLASSIFICATION
IC, IIA, IIC, IVA, VB

[illegible]

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SHELL OIL COMPANY

IMPERIAL IRRIGATI

STATE

1

IC, IIA, IIIC, IVA, VB

FIELD
NILAND

CLASSIFICATION
IC, IIA, IIIC, IV

[illegible]

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**COMPANY
GEOTHERMAL POWER COMPANY**

WELL
KELLY HOT SPRINGS #1

FIELD
CANBY

COUNTY MODOC	STATE CALIFORNIA	CLASSIFICATION ID, IID, IIBb, IVA/B, VA
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GEOTHERMAL WELL LOG CATALOG						PAGE 1 OF 1	
COMPANY						AEROMET NUCLEAR - INEL	
WELL						FIELD	
BRGE #1						RAFT RIVER GEOTHERMAL	
COUNTY						CLASSIFICATION	
CASSIA						ID, IIA/D/E, IIBa, IVA, VA	
STATE						IDAHO	
DATE	TYPE LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING		
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 DENSITY	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		
4/16/75	CALIPER (4 ARM)	4	S.W.S.	5002	3000		
4/6/75	CEMENT BOND LOG	1	S.W.S.	3650	2700		
2/2/75	TEMPERATURE	1-16	S.W.S.	4630	900		
4/6/75	TEMPERATURE	17,18	S.W.S.	5000	900		

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E. G. & G. OF IDAHO

RRGE #4

FIELD RAFT RIVER GEOTHERMAL

CASSIA

IDAHO

CLASSIFICATION
ID, IIA/D/E, IIBa, IVA, VA

[illegible]

GEO THERMAL WELL LOG CATALOG

COMPANY

AEROJET NUCLEAR INEL

WELL

RGR #3

COUNTY

CASSIA

STATE

IDAHO

FIELD

RAFT RIVER GEOTHERMAL

CLASSIFICATION

ID, IIA/D/E, IIBa, IVA, VA

DATE	TYPE LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING
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

PAGE 1 OF 1

E. G. & G. IDAHO, INC.

RRGE # 3

RAFT RIVER GEOTHERMAL

CASSIA

IDAHO

ID, IIA/D/E, IIBa, IVA, VA

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GEOTHERMAL WELL LOG CATALOG						PAGE 1 OF 1	
COMPANY						REYNOLDS ELECTRIC COMPANY & AEROGEL NUCLEAR COMPANY	
WELL						FIELD	
PRGE #2						RAFT RIVER GEOTHERMAL	
COUNTY						CLASSIFICATION	
CASSIA						ID, IIA/D/E, IIBa, IVA, VA	
STATE						IDAHO	
DATE	TYPE LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING		
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		

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GEOTHERMAL WELL LOG CATALOG

PAGE 1 OF 1

COMPANY

REPUBLIC GEOTHERMAL, INC.

WELL

EAST MESA 16-30

FIELD

EAST MESA

COUNTY

IMPERIAL

STATE

CALIFORNIA

CLASSIFICATION

IC, IIA, IIIC, IVA, VB

DATE	TYPE LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING
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)				

PAGE 1 OF 1

REPUBLIC GEOTHERMAL, INC.

EAST MESA

CLASSIFICATION
IC, IIA, IIIC, IVA, VB

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GEOHERMAL WELL LOG CATALOG

PAGE 1 OF 1

COMPANY

REPUBLIC GEOTHERMAL, INC.

WELL

EAST MESA 18-28

FIELD

EAST MESA

COUNTY

IMPERIAL

STATE

CALIFORNIA

CLASSIFICATION

IC, IIA, IIIC, IVA, VB

DATE	TYPE LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING
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	2	S.W.S.	7980	5020
	(SARABAND)				

GEOTHERMAL WELL LOG CATALOG						PAGE 1 OF 1	
COMPANY REPUBLIC GEOTHERMAL, INC.							
WELL 38-30						FIELD EAST MESA	
COUNTY IMPERIAL			STATE CALIFORNIA			CLASSIFICATION IC, IIA, IIIC, IVA, VB	
DATE	TYPE LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING		
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	1	S.W.S.	5668	1204		
	(SARABAND)						
	COMPUTER PROCESSED INTERPRETATION	2	S.W.S.	8930	5480		
	(SARABAND)						
	COMPUTER PROCESSED INTERPRETATION	3	S.W.S.	5000	3800		
	(SARABAND)						

PAGE 1 OF 1

REPUBLIC GEOTHERMAL, INC.

FIELD
EAST MESA

CLASSIFICATION
IC, IIA, IIIC, IVA, VB

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UNITED STATES BUREAU OF RECLAMATION

MESA 6-2

EAST MESA HOLTVILLE

IMPERIAL

CALIFORNIA

IC, IIA, IIIC, IVA, VB[illegible]

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BUREAU OF RECLAMATION

MESA 5-1

FIELD

MESA ANOMALY

COUNTY

STATE

IMPERIAL

CALIFORNIA

CLASSIFICATION
IC, IIA, IIIC, IVA, VB

[illegible]

PAGE 1 OF 2

U. S. BUREAU OF RECLAMATION

MESA ANOMALY

STATE

CALIFORNIA

CLASSIFICATION
IC, IIA, IIIC, IVA, VB

[illegible]

GEOTHERMAL WELL LOG CATALOG						PAGE 2 OF 2	
COMPANY						U. S. BUREAU OF RECLAMATION	
WELL						FIELD	
COUNTY						MESA 31-1 C/T-1	
STATE						MESA ANOMALY	
IMPERIAL						CLASSIFICATION	
CALIFORNIA						IC, IIA, IIC, IVA, VB	
DATE	TYPE LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING		
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)						
8/26/78	COMPENSATED DENSILOG/NEUTRON	1	D.A.	6163	1000		
8/26/78	TEMPERATURE LOG	1	D.A.	6182	125		
8/26/78	ACOUSTIC CEMENT BOND LOG	1	D.A.	6165	1000		
9/6/78	CEMENT BOND with NUCLEAR LOG	1	G.O.	6162	1000		
9/7/78	TEMPERATURE/PRESSURE LOG	1	G.O.	6184	1000		
9/9/78	X-Y CALIPER	1	G.O.	6160	1000		
9/6/78	GAMMA RAY NEUTRON	1	G.O.	6165	1000		
11/29/78	TEMPERATURE LOG	1	McC.	6169	200		
11/29/78	BOND LOG	1	McC.	6160	1000		
11/28/78	CASING INSPECTION	1	McC.	5500	1000		
11/30/78	GAMMA RAY NEUTRON	1	McC.	6166	1000		

GEOTHERMAL WELL LOG CATALOG						PAGE 1 OF 1	
COMPANY						U. S. BUREAU OF RECLAMATION	
WELL						FIELD	
MESA 6-1						MESA ANOMALY	
COUNTY						STATE	
IMPERIAL						CALIFORNIA	
CLASSIFICATION						IC, IIA, IIIC, IVA, VB	
DATE	TYPE LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING		
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)						

PAGE 1 OF 1

BUREAU OF RECLAMATION

MESA ANOMALY

IC, IIA, IIC, IVA, VB

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PAGE 1 OF 1

COMISION DE ENERGIA GEOTERMICA

M-45

CERRO PRIETO

MEXICALI

BAJA, MEXICO	IB, IIA, IIIC, IVA, VB
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PAGE 1 OF 1

LOS ALAMOS SCIENTIFIC LABORATORY

PHILLIPS KDRA 9-1/LASL C/T-2

ROOSEVELT HOT SPRINGS

STATE

UTAH

CLASSIFICATION

IB, IIIC, IIIAa, IVB, VB

[illegible]

GEOTHERMAL WELL LOG CATALOG						PAGE 1 OF 1	
COMPANY						WILDCAT	
WELL						FIELD	
COUNTY						IB, IID, IIIF, IVB	
STATE						CLASSIFICATION	
HAWAII							
KILAUEA TEST HOLE NO. 1							
HAWAII							
DATE	TYPE LOG	RUN NO.	LOG COMPANY	LOWER READING	UPPER READING		
4/20/73	INDUCTION - ELECTRICAL LOG	1	S.W.S.	1030	10		
6/3/73	INDUCTION - ELECTRICAL LOG	2	S.W.S.	3067	1030		
7/9/73	INDUCTION - ELECTRICAL LOG	3	S.W.S.	4090	3079		
4/16/73	COMPENSATED FORMATION DENSITY	1	S.W.S.	910	10		
4/20/73	COMPENSATED FORMATION DENSITY	2	S.W.S.	1026	400		
6/3/73	COMPENSATED FORMATION DENSITY	3	S.W.S.	3068	1027		
7/9/73	COMPENSATED FORMATION DENSITY	4	S.W.S.	4080	2900		
4/16/73	SIDEWALL NEUTRON POROSITY	1	S.W.S.	913	18		
4/20/73	SIDEWALL NEUTRON POROSITY	2	S.W.S.	1027	400		
6/3/73	SIDEWALL NEUTRON POROSITY	3	S.W.S.	3068	1034		
7/9/73	SIDEWALL NEUTRON POROSITY	4	S.W.S.	4192	2900

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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4. PROBLEM DEFINITION AND DIRECTION FOR SOLUTION

To directly investigate the problems in geothermal well log interpretation, four wells were processed using typical state of the art techniques developed within the petroleum industry. Wells having sand/shale lithologies, which normally present fewer problems and unknowns in the course of interpretation than do wells with more complex reservoirs, were not selected for processing. Instead, the four wells selected were chosen because they have formations that are mineralogically complex. The processing of each well is explained in this section, and is followed by a discussion of results, problems, and needed solutions.

GT-2, Hot Dry Rock Program

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 the LASL, the well was designed to test the viability of heat extraction by the HDR technique (see references).

The interval selected for study, 1 905 - 2 027 m (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, and
- Quartz Monzonite; light pink.

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

- Dual Induction - Laterolog,
- Compensated Neutron - Formation Density with Gamma Ray and Caliper, and
- Borehole Compensated Sonic.

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

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

- Lithology,
- Porosity, and
- 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 of approximately 2.52 g/cm^3 , and very low porosity.

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

Figure 4.3 is a crossplot of density and sonic data. This particular crossplot indicates very low porosity. The lithology resolution is poor in the sandstone, limestone, and dolomite regions. 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/sec ($19\,500 \text{ ft/s}$), the sandstone and limestone response lines would nearly coincide, but would represent 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 would be expected from the classical quartz sandstone trend. Because 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 feldspar (travel time = $164 \text{ } \mu\text{s/m}$ ($50 \text{ } \mu\text{s/ft}$)) 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 diagram which represents the model. The neutron values are converted to sandstone units to have 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 (Figs. 4.2, 4.3, and 4.4) indicates the possibility of fracturing (see Section 5.c, Fracture Detection and Definition). 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 verifying 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 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, the 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 Section 5.c.) The output of this program is a term "FRAC" which increases in value with increasing indications of fracturing. Figure 4.7 is a similar crossplot to Fig. 4.6 except that the values of FRAC (a range of 1 to 5) are 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 of fracturing is associated with the rock of lowest grain density. Figure 4.8 is an M-N plot with FRAC in the Z-axis verifying the sonic response in fractured intervals.

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 matrix parameters are well known or may be determined from crossplots. Advantages of this technique are:

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

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

- The matrix parameters are different enough to allow resolution of the data.
- The logs are responding only to lithology and primary porosity. For example, the sonic log must not be influenced by fractures or vugs or mechanical properties of the formation.

These models may also use resistivity data for computing porosity if the following items are known:

- Resistivity of formation water at formation temperature (R_w).
- a and m for the 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.

In well GT-2, sample descriptions and cores were used to identify 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/cm³ and matrix travel time 140 to 250 μ s/m (43 to 76 μ 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 types of rock known to be present. This leads to the calculation of reasonable porosity values. Verification was made for the detection of fracturing by the classical definition of fracture effects on the sonic log.

The enclosed analog playback (Fig. 4.9) shows the result of the described two-mineral model interpretation technique.

Raft River Geothermal Reservoir - RRGE #2

The Raft River Geothermal Reservoir is located in Cassia County in south-central Idaho. The upper 1 402 m

(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 the Raft River Reservoir is dependent on highly fractured zones (Stoker and others).

A 530 m (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:

1 422 - 1 658 m (4 665 - 5 440 ft): Schist, quartzite, etc. (Figs. 4.10 - 4.13).

1 295 - 1 422 m (4 250 - 4 665 ft): Tuffaceous siltstone, etc. (Figs. 4.14 - 4.17).

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 for sandstone and limestone. Distinction between the two can be made by two characteristics. The quartz monzonite (1 524 m (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 response. The quartz monzonite is very radioactive as compared to the quartzite. In fact, it was so radioactive in this well that the gamma ray detector was saturated or recording limits were 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 the use of only two porosity logs can be misleading in lithology interpretation (1 423 - 1 442 m (4 670 - 4 730 ft) on the logs).

Density-Neutron crossplot:

Data plots between limestone and dolomite.

Sonic-Neutron crossplot:

Data plots between sandstone and limestone.

Density-Sonic crossplot:

Data indicates a formation more dense than dolomite and/or with a larger transit time than dolomite.

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

Group 3: Schist

The zone 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 in the studied interval. The transit time is about 164 μ s/m (50 μ s/ft). This zone plots far outside the "standard" lithology lines as shown on Fig. 4.10 (density and neutron crossplot) and Fig. 4.12 (density and sonic crossplot). The neutron-sonic crossplot, however, shows the data to "appear" the same as a 4-5% porosity dolomite. Further details of this interval follow immediately in the discussion of well RRGE #3C where this zone is readily correlatable.

The zone above 1 422 m (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 which usually occurs 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 (Figs. 4.18 and 4.19) are enclosed for comparison to the crossplot data.

Raft River Geothermal Reservoir - RRGE #3C

For this well, crossplots were made over the metamorphic zone, 1 640 - 1 800 m (5 390 - 5 920 ft), which correlates with the zone 1 422 - 1 658 m (4 665 - 5 440 ft) in well RRGE #2. Corresponding plots between the two wells are Figs. 4.10 - 4.13 and Figs. 4.20 - 4.23.

Comparisons of the crossplots between the two wells show both similarities and differences. Both logging suites include a compensated neutron (dual detectors), compensated density, and compensated sonic. They were recorded by two different service companies.

Comparison of Compensated Neutrons:

Both neutron logs were recorded assuming a "sandstone" matrix. The two field recordings are very similar

in magnitude and character. The usual technique, when evaluating formations of a complex nature, is to plot other porosity log recordings against the neutron log, assuming a limestone matrix. This method is used for two reasons: (1) The basic tool calibration is made in limestone test pits and the tool electronics are designed to give a linear response in a limestone formation. (2) One set of standard plots can be generated as a reference for comparison. The conversion from sandstone response to limestone response was made based on the published charts for each of the neutron types. The resulting crossplots show the neutron responses to be quite different in the very low porosity range. This is not a serious problem since a model can be built (as previously demonstrated for GT-2) by selecting the model parameters directly from the individual crossplots. The resulting porosities and indicated lithology of these two wells would then be nearly the same. This does point out very clearly that computations using neutron logs must be individualized for each type of neutron log recorded by each service company. Any field-wide interpretation technique which utilizes crossplots, histograms, etc., must be carefully applied if different types of neutron logs are used.

Comparison of Compensated Density Logs:

Compensated density tools were designed to provide a bulk density value which is corrected for the effect of mudcake. The correction will also compensate for minor hole rugosity, but not for very rough or washed out boreholes. The bulk density readings from these two wells compare very closely in range of values and in character.

Comparison of Compensated Sonic Logs:

Sonic logs are known for their repeatability within a well, and from one well to another. This is primarily due to the type of measurement that is made. The signal is not subject to radioactive statistics, different types of detectors or measurement systems (e.g., thermal or epithermal), or to electronic manipulation designed to match test pit calibrations. However, the differences in the recorded logs between RRGE #2 and RRGE #3C is very striking. (Notice that the sonic scales on the cross-plots are different for the two wells.) There are several possible explanations for these differences.

Geological:

The two wells are approximately 2.2 km (1.3 miles) apart but the correlation from the gamma ray logs is quite obvious. The character of the rock may have changed between the wells, but any such changes would probably have been reflected in the density and/or neutron values. Instead, both the density and neutron logs in each well are very similar to those from the other well.

Recording Errors:

Inspection of calibrations and scales did not verify any type of error in recording techniques. A plot was made to study the possibility of one of the logs recording other than compressional transit time. Figure 4.24 is a plot of compressional vs shear transit times from Section 5.b matrix data. These 60 data values are for all types of rocks and minerals and were not selected to match the minerals and rocks in the metamorphic interval. A statistical line was drawn to indicate a general trend of the data. It is not implied that this line is a substitute for deriving the shear or

compressional transit time from logs. This relationship is a complex function of rock properties and should not be represented by a simple straight line. The grouping of data does, however, have a strong trend and can be used for general direction and magnitude. As the transit time data for both wells were well grouped with very little scatter, average low and average high values were selected. These values are plotted on Fig. 4.24 as the circled data points. The trend strongly indicates the possibility that the transit time recorded on RRGE #3C is for the shear arrival rather than the compressional arrival.

A remark on the RRGE #2 log heading comments on observations of the wavetrain:

"Scope Observation - from 4670 to 6006 ft, compressional wave highly attenuated to the point of being nonexistent. Shear waves are saturated".

A second set of logging tools verified this characteristic. Other explanations for this difference can be considered, but cannot be verified with the available data. This would have had to be done at the time of recording the logs. If both logs are valid, the difference may be an indication of rapidly changing rock strength properties.

Rock Type Identification:

The rock types identified in the discussion of RRGE #2 are easily found on the RRGE #3C crossplots. Group 3 does, however, change character in density and neutron response and gamma ray readings. Keys (1979) suggests the hydrothermal alteration of biotite schist (RRGE #3C) to chlorite (RRGE #2) may account for this.

Raft River Geothermal Reservoir - RRGE #1

A visual review of RRGE #1 logs was made over the metamorphic zone and compared to the logs from RRGE #2.

- The density and neutron logs are comparable,
- The sonic logs are comparable in the upper and very lower sections,
- A 75 m (250 ft) section of the sonic is very "noisy" with sharp spikes reading both too high and too low. The borehole is smooth and in gauge over this "noisy" interval.

Considering RRGE #1, 2 and 3C, the most plausible explanation for the sonic log response is a property of the metamorphic rock that greatly attenuates the compressional amplitude of the acoustical signal. Transmission of a compressional wave across 35° to 80° fractures is reduced considerably more than that for near horizontal or vertical fractures (Morris, and others, 1964). However, the likelihood of such a consistent and extensive fracture system is small. The foliated structure of schists could possibly be another explanation for the attenuation but again, as in the case of fractures, the likelihood is small, and the entire metamorphic section is not schist according to published papers.

Kelly Hot Springs #1

Kelly Hot Springs, located in Modoc County, California, is the largest artesian boiling hot springs in California and the second largest in the United States. Two deep geothermal wells have been drilled in this area. The

well described here was drilled by Geothermal Power Corporation in 1974 to a depth of 1 035 m (3 396 ft). It had a bottom hole temperature, after stabilization, of 115°C (240°F). Plans are under way to utilize the hot water from this reservoir (Class ID in the classification scheme of this report) for agricultural processing.

This region is part of the Modoc Plateau geological subprovince (part of IIIBb according to the classification scheme of this report). It is an area of interfingering Late Tertiary and Quarternary volcanic and sedimentary rocks, broken by sets of north and northwest trending faults. Structurally, the subprovince bears affinity to the Basin and Range province (Class IIIA) to the east. However, geologically, it resembles the Cascade Range subprovince (IIIBb) to the west, with which it shares an uncertain boundary.

A suite of standard open hole well logs (Induction, Compensated Formation Density, Borehole Compensated Sonic, and Temperature) were run in the well (see Fig. 4.36). Descriptions of the drill cuttings provided a crude lithology log for the well. The upper 442 m (1 450 ft) was an alternating sequence of sediments: Sandstone, siltstone, shale, and conglomerate (Class IIA); partially tuffaceous sediments (Classes IIA and IID); and mafic igneous rocks such as basalt flows, diabase sills, or dykes (Class IID). This was marked by steep temperature gradients. Below this section, to about 884 m (2 900 ft) was a sequence of tuffs and tuffaceous sedimentary rocks (Class IIE). This section contains major aquifers, beginning at about 543 m (1 780 ft), and especially from 741-838 m (2 430-2 750 ft). This zone was marked by lost circulation, isothermal

temperature profile (with local reversals), and poor recovery of cuttings. Below this section the rest of the hole was increasingly rich in basalt flows with tuffs and tuffaceous sedimentary rocks present. This section showed less apparent permeability, a low temperature gradient, and some zones of poor recovery of cuttings. Permeability in the well, as indicated by lost circulation and poor cuttings recovery, is of the fracture type (Class IVB), probably associated with one or more major faults in the area and preferentially distributed in siliceous tuffs. Although no water analysis data from the well were available, geologists expect the water to be very similar to that from the boiling pool of Kelly Hot Springs. Expected salinity in this well is 1 000 ppm or slightly higher (Class VA).

Log Analysis Approach

As with most other geothermal wells, the problem of unfamiliar lithology was the greatest hurdle in analyzing the suite of logs from the well. Drill cuttings logs provided a crude lithological profile of the well, with the average interval described being about 9.8 m, (30 ft) thick. As in any well, the cuttings log was unreliable for several reasons:

- Samples could not be collected fast enough during periods of rapid drilling,
- Cuttings from above and below the lost circulation zones had flowed into the zone and did not reach the surface, or had been so thoroughly mixed with the lost circulation material that they could not be recovered,
- The sample collection did not accurately take into account the time required to transfer the cuttings

to the surface. Consequently, the samples collected for the deeper depths are from shallower depths than those indicated on the log,

- Identification of lithology, particularly of igneous rocks with various degrees of alteration, from drill cuttings is a difficult task. Consequently, the drill cuttings description is often not specific enough. No thin section study had been performed; hence, lithologic description of the igneous rocks is quite subjective.

For the purposes of this study, the lithologic description of the cuttings log was accepted as a starting point for lithology evaluation. A scan of the cuttings log showed about nineteen lithologic groups, some of them occurring intermixed in the same interval. For convenience in computer interpretation of data, each of these "lithologic groups" was assigned an alphanumeric code (termed "LITH") as shown in Table 4.1. It should be emphasized that each LITH code does not necessarily represent a unique lithology, but a lithologic assemblage as described from drill cuttings. The main thrust of this study was to diagnose lithology from well logs so that a detailed foot-by-foot lithologic profile could be obtained. The other aims of this analysis were to detect permeable zones; obtain porosity estimates, if possible; and to estimate the static temperature of the reservoir from the maximum temperature recorded during logging. The log data were digitized, edited, corrected for borehole effects, and stored on magnetic tape for computer analysis. Each depth interval was assigned a LITH value based on the drill cuttings data, assuming that all points in a cutting sample interval have the same lithology as represented by LITH. The digitized data covered the interval 259 - 1 021 m (850 - 3 350 ft).

TABLE 4.1

LITHOLOGIC CLASSIFICATION OF SAMPLE DESCRIPTIONS

<u>LITH</u>		<u>DESCRIPTION</u>
I. SEDIMENTARY ROCKS		
	1	Shale and Claystone
	2	Shale and Siltstone
	3	Siltstone
	4	Mudstone
	5	Sandstone and Siltstone
	6	Pebbly Sandstone
	7	Sandstone and Conglomerate
	8	Siliceous Rock Fragments and Crystals
II. PYROCLASTIC ROCKS		
	9	Tuffaceous Sandstone
	A	Tuff
	B	Vuggy Tuff
	C	Tuff with eutaxitic texture
III. IGNEOUS ROCKS		
	D	Basalt
	E	Basaltic Andesite
	F	Basaltic Andesitic Porphyry with Vugs
	G	Latite Porphyry
	H	Latite Porphyry with Vugs
	I	Granodiorite
	J	Unknown Lithologies

In general, SP, electrical resistivity, caliper, and temperature logs were not useful for lithology identification. Sonic, density, and gamma ray logs, together with cuttings descriptions were used for lithology identification.

Histograms of sonic, density, and gamma ray logs showed wide distributions of values with many poorly defined peaks. This is to be expected, considering the complex mixture of lithologies in the well. Because of this, no further use was made of these plots.

Crossplots of density (ρ_b in g/cm^3) vs sonic travel time (Δt in $\mu\text{s/ft}$) for the entire well showed considerable scatter (Fig. 4.25), particularly in the high t and low ρ_b ranges. Nevertheless, a reasonably well-defined linear trend seems to exist for Δt values lower than about 295 $\mu\text{s/m}$ (90 $\mu\text{s/ft}$) and for ρ_b values higher than 2.3 g/cm^3 . This perhaps indicates basic similarities of matrix density and sonic velocity values for the lithologies in this range of Δt and ρ_b in the well. When gamma ray (in API units) is superimposed on this plot as the Z-axis variable (Fig. 4.26), it is seen that the zones on the linear trend mentioned above also seem to display low gamma ray values as compared to the rest of the well. As will be shown later, these high density, high sonic velocity, and low gamma ray zones consist primarily of basaltic andesites and granodiorites. The low gamma ray values for these two lithologies can be traced to their low content of potassium-bearing feldspars and micas.

When LITH values are superimposed as the Z-variable on the density-sonic crossplot, it is possible to identify

trends for individual lithologic groups chosen (Fig. 4.27). However, overlap of the data points belonging to various LITH values makes it difficult to establish trends. Hence, this plot was replaced by four plots (Figs. 4.28 to 4.31) on which data were presented for fewer LITH values. For example, Fig. 4.28 shows data for LITH of 1 through 8, i.e., all sedimentary lithologies. As seen on Fig. 4.28, "shale and claystone" (LITH=1) points plot in the upper right corner and go offscale from that corner. The low ρ_b and high Δt values for these points imply undercompaction of the sediments and the presence of porosity.

"Shale and siltstone" (LITH=2) data points fall in two distinct groupings. The cluster in the upper right corner (LITH=2"a") where Δt is greater than 453 $\mu\text{s/m}$ (138 $\mu\text{s/ft}$) and ρ_b less than 2.1 g/cm^3 , continues offscale. (An "a" or "b" following a LITH code identifies separate clusters of this lithology on a crossplot.) These points represent undercompacted zones which lie in the same depth intervals as LITH=1. The cluster 2"b", between $\rho_b = 2.43 - 2.74 \text{ g/cm}^3$ and $\Delta t = 262 - 177 \mu\text{s/m}$ (80 - 54 $\mu\text{s/ft}$) represents zones in the lowermost parts of the well. This cluster overlies igneous lithology clusters (Figs. 4.30 and 4.31) to be described later. It is possible that the cluster for LITH=2"b" actually represents igneous rocks wrongly identified as shales and siltstones. This is possible, particularly if the rock is weathered and pulverized in the drilling process. Alternately, this cluster may represent sediments with dense pyroclastics. However, the tuffs and tuffaceous rocks from this well show clustering at a much lower ρ_b than for LITH=2"b" (Fig. 4.29); therefore, the pyroclastics in LITH=2"b" zones, if present, must be different than the

tuffs in this well. The possibility of silicification or contact metamorphism of the sediments in the formation of the LITH=2"b" cluster cannot be ruled out. The gamma ray values of this cluster (18-30 API units) appear to be lower than that for LITH=2"a" cluster (36-56 API units). LITH=2"a" zones appear to be porous.

"Siltstones" (LITH=3) was grouped in the $\rho_b = 2.12$ - 2.18 g/cm^3 and $\Delta t = 371$ - $426 \text{ } \mu\text{s/m}$ (113 - $130 \text{ } \mu\text{s/ft}$) ranges with gamma ray values ranging from 39 to 44 API units. These zones also appear to be undercompacted and porous. Another group of LITH=3 points to the left of the main cluster falls in the tuff (LITH=A) cluster (Fig. 4.29) and is thought to be a group of tuffaceous zones misidentified as siltstone.

"Mudstone" (LITH=4) data has two distinct clusters of LITH points (4"a" and 4"b") corresponding to two different zones of mudstone. LITH=4"a" occurs about 122 m (400 ft) above the other, but apparently is not as well lithified. The range of data for LITH=4"a" is ρ_b from 2.22 to 2.40 g/cm^3 and Δt from 348 to $413 \text{ } \mu\text{s/m}$ (106 to $126 \text{ } \mu\text{s/ft}$) with gamma ray values from 44 to 53 API units. LITH=4"b" is described in the cuttings as possibly being "lahar", a purely pyroclastic mudstone produced from "a landslide or mudflow of pyroclastic material on the flank of a volcano" (American Geological Institute, 1976). It has a range of data values from ρ_b of 2.34 to 2.42 g/cm^3 and Δt from 226 to $259 \text{ } \mu\text{s/m}$ (69 - $79 \text{ } \mu\text{s/ft}$). Gamma ray values for LITH=4"b" vary from 62 to 70 API units.

"Sandstone and siltstone" (LITH=5) have a narrow range of data values of $\rho_b = 2.13$ - 2.22 g/cm^3 and $\Delta t = 430$ - $446 \text{ } \mu\text{s/m}$ (131 - $136 \text{ } \mu\text{s/ft}$). Gamma ray values are from 37

to 43 API units. The sandstone is apparently not well compacted and probably has high porosity. Some LITH=5 data points are scattered outside the LITH=5 cluster, most of them plotting inside or near the siltstone (LITH=3) data cluster. They are most likely siltstone, leaving the possibility that the LITH=5 cluster represents only sandstone zones.

LITH=6 ("pebbly sandstone") does not have enough data points to define any lithologic characteristics. The same is true of LITH=7 ("sandstone and conglomerate").

Siliceous rock fragments and crystals (LITH=8) data plot in a well-defined zone limited to a narrow band with $\rho_b = 2.38-2.71 \text{ g/cm}^3$ and $\Delta t = 262-197 \text{ } \mu\text{s/m}$ (40-60 $\mu\text{s/ft}$). Gamma ray values for LITH=8 vary from 15 to 29 API units. The data points for "siliceous rock fragments and crystals" overlap data points for shale and siltstone (LITH=2"b"), "mudstone" or "lahar" (LITH=4"b"), "basaltic andesite" (LITH=E, Fig. 4.30), and also "granodiorite" (LITH=I, Fig. 4.31).

Tuffaceous lithologies showed a wide range in log response. Figure 4.30 shows the wide spread of data points for "tuffaceous sandstone" (LITH=9), "tuff" (LITH=A), "vuggy tuff" (LITH=B), and "tuff with eutaxitic (welded) texture" (LITH=C). Comparison of Figs. 4.28 and 4.27 shows that many of the sedimentary and tuffaceous lithology points overlap, possibly because of the difficulty in estimating the relative content of tuffaceous materials in sedimentary rock cuttings.

"Tuff" (LITH=A) data points plot over an area with $\rho_b = 2.00-2.39 \text{ g/cm}^3$ and $\Delta t = 384-230 \text{ } \mu\text{s/m}$ (117-70 $\mu\text{s/ft}$). Gamma ray values seem to increase from upper right to

lower left, varying over 35-65 API units. In tuffaceous rocks and basalts from this well, the gamma ray response seems to increase as density increases. The reason for this behavior is not clear.

"Vuggy tuff" (LITH=B) points are dispersed through the "tuff" (LITH=A) points and are not readily differentiable from tuff. "Welded tuff" (LITH=C) has a localized trend of data points extending from $\rho_b = 2.31 \text{ g/cm}^3$ and $\Delta t = 367 \text{ } \mu\text{s/m}$ (112 $\mu\text{s/ft}$) to 2.48 g/cm^3 and $\Delta t = 299 \text{ } \mu\text{s/m}$ (91 $\mu\text{s/ft}$). Gamma ray values for "welded tuff" vary from 35 to 65 API units. The somewhat linear trend of the LITH=A and LITH=C clusters could be caused by a varying range of porosities in these zones. The zones with Δt greater than about 110 $\mu\text{s/ft}$ possibly are undercompacted and highly porous. This observation agrees with the fact that a great deal of lost mud circulation was experienced while drilling through the tuffaceous sections of the well. This is indicative of the presence of convecting aquifers.

The igneous rocks have the tightest data point cluster of any of the lithologies in the Kelly Hot Springs #1 Well (Fig. 4.30). For example, "basalt" (LITH=D) has a fairly well defined point cluster with a range of values of $\rho_b = 2.30\text{--}2.42 \text{ g/cm}^3$ and $\Delta t = 276\text{--}335 \text{ } \mu\text{s/m}$ (84-102 $\mu\text{sec/ft}$). Gamma ray values vary widely, however, from 30 to 70 API units. Several types of basalt may exist within this data point cluster, as two subgroupings of data can be seen. The subgroup to the lower left has gamma ray values of 30-55 API units while those to the upper right have values of 30 to 70 API units.

Other data points described as basalt in cutting samples plot in a tight cluster of points with an average value of $\rho_b = 2.42 \text{ g/cm}^3$ and $\Delta t = 177 \text{ } \mu\text{s/m}$ (54 $\mu\text{s/ft}$). However, data called "basaltic andesitic porphyry with vugs" (LITH=F) also plot around the same average data point. The low bulk density and high travel time support the idea of vugs. The data points plotting in the cluster called LITH=D are probably, in fact, "basaltic andesitic porphyry with vugs" and should be classified as LITH=F.

The majority of "basaltic andesite" (LITH=E) is seen on the crossplot (Fig. 4.30) as a dense cluster of points covering $\rho_b = 2.77\text{-}2.84 \text{ g/cm}^3$ and $\Delta t = 171\text{-}184 \text{ } \mu\text{s/m}$ (52-56 $\mu\text{s/ft}$). This rock has the highest density and the fastest travel time of any of the lithologies described in the well. A long thin band of LITH=E data extends toward the upper right corner from the densest point cluster. It is unclear whether this is also "basaltic andesite" which has undergone some changes (weathering, hydrothermal alteration, etc.); a different lithology interbedded with the "basaltic andesite"; or "basaltic andesite" with varying amounts of porosity. Gamma ray readings for the dense LITH=E cluster range from 24 to 32 API units.

In Fig. 4.31, the remaining lithologies are cross-plotted. "Latite porphyry" (LITH=G) has good crossplot definition, with all data points falling in the range of $\rho_b = 2.16\text{-}2.28 \text{ g/cm}^3$ and $\Delta t = 295\text{-}318 \text{ } \mu\text{s/m}$ (90-97 $\mu\text{s/ft}$). Gamma ray values, however, vary from 35 to 75 API units. "Latite porphyry" with vugs (LITH=H) has a much faster travel time, $\Delta t = 266\text{-}279 \text{ } \mu\text{s/m}$ (81-85 $\mu\text{s/ft}$), with a slightly heavier bulk density ($\rho_b = 2.21\text{-}2.30 \text{ gm}^3$).

Gamma ray values for LITH=H are 45-65 API units. Both LITH=G and LITH=H fall completely within the tuff (LITH=A) data and are completely obscured by it in Fig. 4.27.

"Granodiorite" (LITH=I, Fig. 4.31) has a well defined tight cluster with $\rho_b = 2.60-2.66 \text{ g/cm}^3$ and $\Delta t = 203-230 \text{ } \mu\text{s/m}$ (62-70 $\mu\text{s/ft}$) and gamma ray values of 5-10 API units. These values are in good agreement with those of typical granitic rocks; the low gamma ray values being an indication of a lack of potassium feldspars in the rock. The rest of the points in Fig. 4.31 with LITH=J represent zones for which lithology has not been identified from cuttings. It appears from crossplots that these zones are tuffaceous sediments.

Using the typical responses of the various lithologic groups as deciphered from trends of crossplot data points, it is possible to identify the lithology of any zone in the well. Unfortunately, any quantitative estimate of lithology will be impossible because of the multitude of various lithologies.

Porosity and Permeability

Since it was not possible to evaluate the lithologies of each zone quantitatively, it is difficult to calculate the porosities of various zones accurately. However, a few general deductions regarding porosity have been made. For example, all sedimentary and tuffaceous zones that were described as undercompacted are likely to be porous; but, whether or not they are permeable cannot be said. The drilling record shows considerable lost circulation and loss of cuttings in the tuffaceous zones. Hence, it is likely that the roughly linear

spread of data points in Fig. 4.29 for compacted tuffaceous zones is a reflection of the porosity variation in these rocks. Even basaltic rocks in Fig. 4.30 show a linear trend, perhaps indicating the presence of porosity in these rocks. Since fracture porosity may not affect sonic travel time, the porosity, if any, in these rocks may be of a vesicular type. Vesicular porosity in these volcanic rocks is common. By careful comparison of caliper and temperature logs with drilling history and with sonic and density data, it is possible to identify the porous zones. In general, the caliper log will show hole enlargement in fractured and/or highly porous (sedimentary) sections. The temperature profile often shows anomalies in porous zones.

Mechanical Strength

Mechanical strength of rocks can be approximately evaluated from well logs. Mechanical strength of rocks sometimes may be used to differentiate between lithologies. For example, it can be used to distinguish between a sediment and its metamorphosed, and usually hardened, equivalent. Also, mechanically strong rocks can undergo and sustain brittle fracturing and therefore have a higher probability of fracture permeability.

An approximate index of the mechanical strength of a rock is given by the parameter:

$$MSI = \frac{p_b}{\Delta t^2} \times 10^5 \quad (4.1)$$

The higher the value of MSI, the stronger the rock. Figure 4.32 shows MSI for all the zones in the Kelly Hot

Springs #1 well plotted against corresponding caliper readings. The figure shows that for zones with a MSI greater than about 20, the caliper reading is practically independent of rock strength. But for weaker rocks (MSI less than 20), the caliper readings increase as MSI decreases. This can be explained by the fact that in weaker rock sections, the hole may slough and become enlarged, while competent rocks, unless fractured, will not allow hole enlargement.

Figure 4.33 shows the plot of MSI versus depth for all zones. A general trend of increasing mechanical strength with depth is evident in the lower half of the plot. It should be noted that this trend is formed primarily by sedimentary (LITH=1-8) and tuffaceous (LITH=9-C) lithologies. This is expected because sediments and pyroclastics at greater depths are more compacted and hence, stronger. Several point clusters with basaltic lithologies (LITH=D-F) and granodiorite (LITH=I) stand out in several intervals as being much stronger than expected from the general trend. These clusters represent zones that may have brittle fractures; however, the mere presence of rock strength does not assure the presence of fractures.

Estimation of Formation Temperature

Attempts were made to estimate true formation temperature using data obtained during logging runs. Table 4.2 presents these data compared with the data from a temperature log. The operator of the Kelly Hot Springs well used this data to obtain the true formation temperature as shown below. (F. Metcalfe, 1979)

The mathematical relationship between the temperature recovery when the well is shut in and heat removal from a formation during circulation can be represented as:

$$T_i - T_{ws} = \frac{q}{2\pi Kh} [T_D(t_p + \Delta t) - T_D(\Delta t)] \quad (4.2)$$

where:

- T_i = true formation temperature, °C (°F)
- T_{ws} = shut-in temperature, °C (°F)
- q = constant rate of heat removal from the formation during circulation, calories/sec (Btu/hr)
- K = thermal conductivity of formation, calories/sec-cm-°C (Btu/hr-ft-°F)
- h = formation thickness, cm (ft)
- t_p = circulation time, sec (hr)
- Δt = shut-in time, sec (hr)
- T_D = dimensionless heat flow function that relates the heat flow to changes in temperature in space and time. (Edwardson and others, 1962)

Edwardson and others (1962) give T_D values for various values of dimensionless time, t_D , defined as:

$$t_D = \frac{Kt}{C_p \rho r_w^2} \quad (4.3)$$

where:

- t = real time, sec (hr)
- C_p = specific heat of formation, calories/gm/°C (Btu/lb/°F)

TABLE 4.2

SUMMARY OF RELEVANT TEMPERATURE DATA
 KELLY HOT SPRINGS NO. 1
 (July 14, 1974)

DATE	TIME AT TD (P.D.T.)	LOG RUN	TEMP. FROM MAX.READ. THERMOMETER		MAX. TEMP. FROM TEMP. LOG	
			°C	°F	°C	°F
7/13/74	1300	Temp. 1	68	(154)	76	(169)
7/13/74	1345	Induction-ES	70	(158)	76	(169)
7/13/74	1530	Density	74	(165)	76	(169)
7/13/74	1735	Sonic	77	(170)	76	(169)
7/13/74	2305	Temp. 2	84	(183)	85	(185)
7/14/74	0700	Temp. 3	90	(194)	85	(185)
7/14/74	1400	Depth. Det.	94	(202)	85	(185)

TABLE 4.3

SUMMARY OF CALCULATIONS OF HEAT FLOW FUNCTION

$[T_D(t_D) - T_D(t_D')]$
 KELLY HOT SPRINGS NO. 1
 (July 13/14, 1974)

DATA NO.	TOTAL TIME SINCE CIRCULATION NEAR TD STARTED t (hrs.)	TIME SINCE CIRC. STOPPED t' (hrs.)	T_D	$T_{D'}$	$T_D(t_D)$	$T_D(t_{D'})$	$[T_D(t_D) - T_D(t_{D'})]$	TEMPERATURE °C (°F)	
1	16.0	4.0	4.3	1.1	1.30	0.83	0.47	68	(154)
2	16.8	4.8	4.5	1.3	1.32	0.88	0.44	70	(158)
3	18.7	6.7	5.0	1.8	1.36	0.99	0.37	74	(165)
4	20.8	8.8	5.6	2.4	1.41	1.09	0.32	77	(170)
5	26.3	14.3	7.1	3.9	1.51	1.27	0.24	84	(183)
6	34.3	22.3	9.3	6.0	1.62	1.44	0.18	90	(194)
7	41.3	29.3	11.2	7.9	1.70	1.55	0.15	44	(202)

Note: Values of dimensionless time are calculated from the formula $t_D = \frac{K}{C_p \rho r w^2} \Delta t = 0.27 t$.

ρ = formation density, g/cm³ (lb/ft³)
 r_w = well bore radius, cm (ft)

The shut-in temperature, T_{ws} will become equal to the true formation temperature, T_i , only if $T_D(t_p + \Delta t)$ is equal to $T_D(\Delta t)$ in Eq. (4.2). At infinite shut-in time compared to circulation time, $t + \Delta t \approx t$ and hence $T_i \approx T_{ws}$. Equation (4.2) shows that if the measured shut-in temperature values at various shut-in times are plotted against the function $T_D(t_p + \Delta t) - T_D(\Delta t)$, the points should fall on a straight line. The intercept of this line at $T_D(t_p + \Delta t) - T_D(\Delta t) = 0$ gives the true formation temperature. Theoretically, T_{ws} will never reach T_i because $t_p + \Delta t$ will never be truly equal to Δt . However, the method should be accurate enough for practical purposes.

This method was used to calculate the true formation temperature of the Kelly Hot Springs No. 1 well. The calculation steps are shown in Table 4.3 for the seven data points shown in Table 4.2. Figure 4.34 shows the plot and the extrapolated straight line giving a true formation temperature of 109°C (228°F). The reason for the deviation from a straight line for points 1 through 4 was the deviation of the actual operating conditions from the assumed model. Also, it should be pointed out that this extrapolation approach provides a pessimistic estimate of temperature. Refer to subsection 5.d of this report for a discussion of the limitations of such an approach. Figure 4.35 shows the temperature profile in the well as measured by a temperature probe.

General Discussion

Problem Definition and Direction for Solution

An analysis of a sand/shale sequence was not made in this study because techniques for the interpretation of this type of formation have been covered extensively within the petroleum industry. This is not to say that all problems are resolved in sand/shale sequence analyses, but the state of the art is far more advanced than that for the analysis of complex rocks. The most difficult remaining problem is the reliable evaluation of permeability.

A computer processed interpretation technique for predicting hydrocarbon production has recently been under study by Schlumberger Well Services (Display booth, SPWLA, Twentieth Annual Logging Symposium, Tulsa, Oklahoma, 1979). Coates and Dumanoir (1973) describe the method for estimating the permeability that is used in the calculations. At present, this technique has been successfully applied in certain study areas and indicates an advancement in the state of the art for this long-standing problem.

The state of the art interpretation techniques for complex lithology were primarily developed for use in mixtures of limestone, dolomite, sandstone and anhydrite. These are common rocks encountered in the oil and gas industry. Of course, many adaptations and special models are routinely made for mixtures containing pyrite, tuff, etc. and for mineral applications such as potash, sulfur, coal, etc. Hydrocarbon exploration and development is also sometimes carried out in areas containing different or complex rocks. Two examples are: a lower

Pennsylvanian igneous sill in the Dineh Bi Keyah field of northeastern Arizona, and the fractured Tertiary agglomerates (ash flows) at Trap Springs, Nevada (Basin and Range). Interpretation of well logs from these provinces is certainly not a cut-and-dried procedure.

The occurrence of these types of lithology are exceptions in the petroleum industry but are commonplace in the geothermal industry. To date, geothermal well log interpretation in these complex rocks has largely consisted of crossplotting whatever data is available in order to define lithology. This technique may at first appear to be an over-simplification of a complex problem, but it is the key to model development for further computations. To determine permeability, porosity must be known and to determine porosity, lithology must be known, in order to specify the matrix response of the logging tools being used. These crossplot techniques, then, hold the key to determining several formation parameters that are important to the geothermal industry. The crossplotting of sonic, density, and neutron data is basic. The use of other measurements is needed to provide additional resolution of rocks with similar responses. Such additional measurements are resistivity, total gamma ray, spectral gamma ray, or any other measurement the analyst can exploit. 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).

Efforts for advanced development of geothermal well log interpretations should be directed toward lithologic identification by the establishment of tool response and matrix characteristics for the major rocks encountered.

Fig. 4.1. Density-neutron crossplot, GT No.2.

WELL NUMBER 29002 LOGCALC RESULTS
 0 DRUP TOP OF INTERVAL (TOPD) = 6250.00 BOTTOM OF INTERVAL (BUTD) = 6650.00

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

Fig. 4.2. Sonic-neutron crossplot, GT No.2.

Fig. 4.3. Density-sonic crossplot, GT No.2.

Fig. 4.4. M-N crossplot, GT No.2.

Fig. 4.5. Two mineral model, GT #2.

Fig. 4.6. Apparent matrix crossplot, GT No.2.

Fig. 4.7. Apparent matrix z-plot (FRAC), GT No.2.

Fig. 4.8. M-N z-plot (FRAC), GT No.2.

Fig. 4.10. Density-neutron crossplot (metamorphic zone), RRGE No.2.

WELL NUMBER 29004
1 DRUP

LOCAL RESULTS
TOP OF INTERVAL (TOD) = 4665.00

BOTTOM OF INTERVAL (BOD) = 5990.00

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*

Fig. 4.11. Sonic-neutron crossplot (metamorphic zone), RRGE No.2.

Fig. 4.12. Density-sonic crossplot (metamorphic zone), RRGE No.2.

Fig. 4.13. M-N crossplot (metamorphic zone), RRGE No.2.

Fig. 4.14. Density-neutron crossplot (sedimentary zone), RRGE No.2.

Fig. 4.15. Sonic-neutron crossplot (sedimentary zone), RRGE No.2.

Fig. 4.16. Density-sonic crossplot (Sedimentary zone), RRG# No.2.

LOGCALC RESULTS
 WELL NUMBER 29004
 1 DRUP
 TOP OF INTERVAL (TOD) = 4250.00
 BOTTOM OF INTERVAL (BTD) = 4664.50

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+

Fig. 4.17 M-N crossplot (sedimentary zone), RRGE No.2.

Fig. 4.20. Density-neutron crossplot (metamorphic zone), RRG# No.3C.

WELL NUMBER 29005 LOGGALC RESULTS TOP OF INTERVAL (TOP) = 5391.00 BOTTOM OF INTERVAL (BOT) = 5920.00
1 DRILL

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 *
THFN COUNT = 5 10 15 20 25 30 35 36+

Fig. 4.21. Sonic-neutron crossplot (metamorphic zone), RRGE No.3C.

Fig. 4.22. Density-sonic crossplot (metamorphic zone), RRGE No.3C.

WELL NUMBER 29005
1 DRILL

LOGCALC RESULTS
TOP OF INTERVAL (TOD) = 5391.00

BOTTOM OF INTERVAL (BOD) = 5920.00

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+

Fig. 4.23. M-N Crossplot (metamorphic zone), RRGE No.3C.

Fig. 4.24. Compressional and shear transit times.

Fig. 4.25. Density-sonic crossplot, Kelly Hot Springs No. 1.

Fig. 4.26. Density-sonic z-plot (gamma ray),
Kelly Hot Springs No.1.

Fig. 4.27. Density-sonic z-plot (LITH),
Kelly Hot Springs No.1.

Fig. 4.29. Density-sonic z-plot (LITH=9 to C),
Kelly Hot Springs No.1.

Fig. 4.30. Density-sonic z-plot (LITH=D to F),
Kelly Hot Springs No.1.

Fig. 4.31. Density-sonic z-plot (LITH = G to J),
Kelly Hot Springs No.1.

Fig. 4.32. MSI-caliper crossplot, Kelly Hot Springs No.1.

Fig. 4.33. MSI-depth z-plot (LITH), Kelly Hot Springs No.1.

Fig. 4.34. Estimate of maximum temperature,
Kelly Hot Springs No. 1.

Fig. 4.35. Temperature profile
Kelly Hot Springs No. 1.

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5. REFINEMENT OF EXISTING INTERPRETATION TECHNIQUES AND DEVELOPMENT OF NEW ONES

5.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 related to its fluid storage and flow capacities, as well as 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.

The Matrix Component

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 and has a strong influence on the log response of a formation, because the volume of matrix material is usually much larger than the fluid volume in the formation. Matrix properties are also affected by temperature and pressure.

Most matrix materials encountered in logging are electrically nonconductive. One notable exception is

shale, because the wet clay minerals in shale can impart considerable electrical conductivity to the matrix. Other exceptions are graphite and metallic minerals, such as pyrite, which are electrically conductive. The conductivity of wet clays is due to ionic double-layer conductivity while that of metallic minerals is due to electronic conduction. The conductivity of shales can vary considerably depending upon the composition of the shale. The conductivity of pure metallic minerals is less variable. The relative arrangement and amounts of the conductive and nonconductive components of a formation matrix determine the overall conductivity of the matrix; therefore, 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 the relative conduction 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 characteristics of the matrix components. Matrix properties such as matrix 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 completely independent of component arrangement.

Matrix Parameters in Response Equations

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

$$A = A_f(\phi) + A_{ma} (1 - \phi) \quad , \quad (5.a.1)$$

where A denotes a physical property (such as sonic travel time, bulk density, neutron porosity, neutron capture cross section, or 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

$$A_{ma} = \sum_{i=1}^n A_{ma,i} X_i \quad , \quad (5.a.2)$$

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

Similarly, if there is more than one fluid, such as oil, gas, or and water in a petroleum reservoir, A_f in Eq. (5.a.1) is given by

$$A_f = \sum_{i=1}^n A_{f,i} S_i \quad , \quad (5.a.3)$$

where $A_{f,i}$ denotes the physical property and S_i the fraction of the pore volume saturated by the i th fluid phase. In geothermal systems, in the usual case, only water is present in the formation within the zone of investigation of the logs. However, the presence of a steam-water mixture or a mixture of gases and water in the formation has been reported from some geothermal areas.

In Eq. (5.a.1), A is read from a log, and A_f and A_{ma} values are usually obtained from tables based on laboratory data. Porosity can then be calculated. However, if the matrix has more than one component, the matrix volume fractions (X_i 's) of the various components must be known before Eq. (5.a.1) can be used to calculate porosity. If n logs are available, n equations of an expanded form of Eq. (5.a.1) can be set up and solved for n unknowns plus porosity when combined with the material balance relationship

$$1 = \phi + X_1 + X_2 + \dots + X_n . \quad (5.a.4)$$

Although linear response equations are more amenable to simultaneous solution of multiple log responses, the form of Eq. (5.a.1) need not be linear in every case. For example, the response equation for the neutron log may be nonlinear in the low porosity range.

Neutron Log:

In geothermal systems, Eq. (5.a.1) may need to be modified. For example, the usual response equation for the neutron log, neglecting excavation effect (see Schlumberger, 1972), is

$$\phi_N = \phi_{N,f} \cdot \phi + \phi_{N,ma} (1-\phi) \quad , \quad (5.a.5)$$

where ϕ_N is the observed neutron log response, $\phi_{N,f}$ the neutron log response from the fluid, $\phi_{N,ma}$ the neutron log response from the matrix, and ϕ the porosity. In Eq. (5.a.5), $\phi_{N,f}$ is usually taken as unity because the pores are water-filled. However, estimating a value for $\phi_{N,ma}$ for a geothermal formation may be difficult. In petroleum reservoir rocks, $\phi_{N,ma}$ has a value close to zero. For example, Schlumberger's SNP has a sandstone matrix response of -0.035, and a dolomite matrix response of +0.035 when the total response is matched to limestone. The value of $\phi_{N,ma}$ can be obtained from logging manuals. The situation is more complicated in many geothermal formations for two reasons

- Because of the presence of many different lithologies, A_{ma} in Eq. (5.a.1) has to be estimated by use of Eq. (5.a.2) in which all X_i 's and $A_{ma,i}$'s are usually not known.
- The presence of hydrated minerals, even in relatively small amounts, can mask the log response from the fluid and make an accurate calculations of ϕ difficult.

Since neutron log response is proportional to the amount of hydrogen atoms in the formation, both free water filling the pore spaces and chemically bound water in a hydrated mineral will affect the log. Hence, assuming a linear response, Eq. (5.a.5) may be rewritten as

$$\phi_N = \phi_{N,f} \phi + \phi_{N,ma} (1-\phi-V_h) + \phi_{N,h} V_h \quad , \quad (5.a.6)$$

where $\phi_{N,h}$ is the neutron log response to the hydrated mineral and V_h the bulk volume fraction of the hydrated mineral in the matrix. In many evaporite deposits, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is known to occur in the matrix. In such cases, the neutron log requires correction for the water of crystallization. However, it should be noted that the use of Eq. (5.a.6) is equivalent to considering a two component matrix -- an anhydrous component (subscript 'ma') and a hydrated component (subscript 'h') -- and using Eq. (5.a.6). If there is more than one hydrated mineral, Eq. (5.a.6) should have more terms. In reality, either the response of each hydrated mineral or its concentration within a particular well section may not be known. In low porosity hydrothermally altered geothermal wells, porosity derived from the neutron log by Eq. (5.a.5) is often too optimistic. An example follows.

Assume a sandstone containing 5% disseminated gypsum with a neutron response of 0.20 (limestone units) using Schlumberger's sidewall neutron porosity log. Then in Eq. (5.a.6), we would have

$$\begin{aligned}\phi_N &= 0.20 \\ \phi_{N,ma} &= -0.035 \\ V_h &= 0.05 \\ \phi_{N,h} &= 0.49.\end{aligned}$$

$$\begin{aligned}\text{Then } \phi &= \frac{\phi_N - \phi_{N,ma} - \phi_{N,h}V_h + \phi_{N,ma}V_h}{\phi_{N,f} - \phi_{N,ma}} & (5.a.7) \\ &= 0.202 \text{ the true porosity value.}\end{aligned}$$

Rearranging Eq. (5.a.5) and solving for the apparent porosity:

$$\phi_a = \frac{\phi_N - \phi_{N,ma}}{\phi_{N,f} - \phi_{N,ma}} \quad (5.a.8)$$

= 0.227, which is 12.4% higher than true ϕ .

Thus by not taking into account the presence of a hydrated mineral, an error of 12.4% is made. Such errors will be greater for higher values of $\phi_{N,h}$ and lower porosity values. For example, in the above-mentioned example, if $\phi_N=0.05$, then true $\phi=0.057$ and $\phi_a=0.082$, giving an error of 43.9%.

In "tight" geothermal rocks, the conventionally calculated porosity values may be entirely due to the response of hydrated minerals. For example, if in the above-discussed case, the rock had zero true porosity, the neutron response would have been $\phi_N=-0.009$ and the calculated apparent porosity would have been $\phi_a=0.025$.

Combining Eqs. (5.a.7) and (5.a.8) we find that:

$$\phi = \frac{\phi_a - V_h (\phi_{N,h} - \phi_{N,ma})}{\phi_{N,f} - \phi_{N,ma}}, \quad (5.a.9)$$

Since $\phi_{N,f}$, $\phi_{N,h}$, $\phi_{N,ma}$ for all hydrated minerals, $\phi = \phi_a$ if $V_h = 0$. Therefore, calculation of porosity from a neutron log ignoring hydrated minerals will always cause overestimation by an amount given by $V_h (\phi_{N,h} - \phi_{N,ma}) / (\phi_{N,f} - \phi_{N,ma})$ and the percent of overestimation will increase as porosity decreases.

It is easier to analyze drill cuttings or core samples to obtain the weight fraction of bound water (W_b) in the matrix than to identify individual hydrated minerals and their $\phi_{N,L}$ and V_h . Once W_b is measured, the bulk volume fraction of the boundwater (ϕ_b) is given by:

$$\rho_b = \rho \cdot W_b , \quad (5.a.10)$$

where ρ_b is the bulk density of the formation (Nelson and Glen, 1975). Then another form of Eq. (5.a.6) will be:

$$\rho_N = \rho_{N,f} \cdot \rho + \rho_{N,ma} (1 - \rho - \rho_b) + \rho_{N,w} \cdot \rho_b , \quad (5.a.11)$$

where $\rho_{N,ma}$ is the neutron response of the matrix without bound water and $\rho_{N,w}$ is the neutron response of bound water. Since $\rho_{N,f} = \rho_{N,w} = 1$,

$$\rho_N = \rho + \rho_b + \rho_{N,ma} (1 - \rho - \rho_b) . \quad (5.a.12)$$

For old model neutron tools, the response is given in API units instead of porosities. For these tools, Eq. (5.a.5) is replaced by the following nonlinear response equation:

$$N = A + B \log \rho , \quad (5.a.13)$$

where N is the neutron deflection (in API units) and A and B are empirical parameters determined by calibration against responses in known porosities. A and B depend on the rock type and fluid content.

For the matrix containing bound water, Nelson and Glen (1975) showed empirically that the following response equation is valid:

$$N = C + D \log(W) , \quad (5.a.14)$$

where W is the weight percent water (pore water plus bound water) and C and D are empirical parameters depending on rock type.

Density Logs:

To calculate porosity from the density log, Eq. (5.a.1) can be written as:

$$\rho_b = \rho_f \phi + \rho_{ma}(1-\phi) \quad , \quad (5.a.15)$$

where ρ_b = observed density log response
 ρ_f = formation fluid density, and
 ρ_{ma} = density of the matrix

If a small amount of "heavy" minerals such as pyrite occurs in a geothermal formation, the ρ_{ma} used in Eq. (5.a.15) should be modified to include the effect of the heavy mineral. When a heavy mineral is present, Eq. (5.a.15) may be rewritten as

$$\rho_b = \rho_f \phi + \rho_{ma} (1-\phi-V_h) + \rho_h V_h \quad , \quad (5.a.16)$$

where ρ_h is the apparent bulk density of the heavy mineral as measured by the logging tool and V_h is its amount expressed in bulk volume fraction of the matrix. Knowing ρ_h and V_h , corrections can be made to the density response for the heavy mineral effect. The value of ρ_h can be estimated from the density log response if an interval containing only the heavy mineral exists in the well.

Let us consider an example. Suppose a granite section with a matrix density of 2.65 g/cm^3 contains a pyritic zone of 5% pyrite concentration and the density log reading in that zone is 2.64 g/cm^3 . Then $\rho_{ma}=2.65$, $V_h=0.05$, $\rho_h=5.0$ (from tables), $\rho_b=2.64$ and $\rho_f=1.0$. After rewriting Eq. (5.a.16). the true porosity is given by:

$$\begin{aligned}\phi &= \frac{\rho_{ma} - \rho_{ma} V_h + \rho_h V_h - \rho_b}{\rho_{ma} - \rho_f} \\ &= 0.077 .\end{aligned}\tag{5.a.17}$$

If the presence of the heavy mineral is ignored, then the apparent porosity from Eq. (5.a.15) is:

$$\begin{aligned}\phi_a &= \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \\ &= 0.008, \text{ which is a drastic underestimation.}\end{aligned}\tag{5.a.18}$$

Obviously, the underestimation of porosity due to ignoring heavy mineral content will be more severe as V_h and/or ρ_h increase. From Eqs. (5.a.17) and (5.a.18) we get

$$\phi = \frac{\phi_a + V_h (\rho_h - \rho_{ma})}{\rho_{ma} - \rho_f},\tag{5.a.19}$$

Since $\rho_h > \rho_{ma} > \rho_f$ for all heavy minerals, $\phi > \phi_a$ if $V_h > 0$. Therefore, ignoring heavy minerals will cause underestimation in the porosity calculation from a density log, with the amount of underestimation being $V_h (\rho_h - \rho_{ma}) / (\rho_{ma} - \rho_f)$ and the percent of underestimation becoming greater as the porosity becomes lower.

Estimation of Matrix Parameters

It is obvious that 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 have been insufficient or nonexistent for most of the lithologies encountered in geothermal reservoirs.

One objective of this project has been to improve the availability of matrix data and in the next section of the report, we have presented an exhaustive compilation of matrix data gathered from the literature and from other sources.

There are essentially four ways of estimating matrix properties:

- Calculation from theoretical considerations,
- Laboratory measurement,
- Derivation from log response in "tight" zones,
- Calculation from multi-log suites.

It should be remembered that laboratory-derived data reported in the literature are usually obtained under ambient conditions, while reservoir conditions are different -- the pressure and temperature are higher and the stress factors are not the same. 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 multi-log suite is available, one can set up a number of linear response equations, as explained earlier. 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 in 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 matrix densities of both components are known. Such estimates can often be made with the help of logging charts or crossplots. For example, in the analysis of sand/shale lithology, the so-called "clay" or "shale" point defined on the density-neutron crossplot represents the matrix responses of the clay or shale matrix.

Matrix properties can be estimated by theoretical means also. Such an estimate is usually a crude approximation because tool response cannot usually be rigorously taken into account. For example, Edmundson and Raymer (1979) presented theoretical equations for the calculation of matrix properties for several logging tools.

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:

$$V_{sh} = \frac{GR - GR_{sd}}{GR_{sh} - GR_{sd}} \quad (5.a.20)$$

where GR , GR_{sd} , and GR_{sh} are the gamma ray intensities of the zone under study, of sand, and of shale, respectively. Equation (5.a.15) tends to overestimate V_{sh} . A more accurate version of the model gives:

$$V_{sh} = \frac{GR \rho_b - GR_{sd} \rho_{sd}}{GR_{sh} \rho_{sh} - GR_{sd} \rho_{sd}} \quad (5.a.21)$$

where ρ_b 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 from which GR_{sd} and GR_{sh} are read. Although an improvement, this calculated V_{sh} may also be too high (Dresser Atlas, 1977).

The SP log measures the spontaneous potential, which consists of the electrochemical potential and, under certain conditions, the streaming potential. 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 is 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

$$C = \sum_{i=1}^n C_i W_i \quad , \quad (5.a.22)$$

where C_i and W_i are the specific heat and the mass fraction (in the matrix), respectively, of the i th component, and

n is the number of components. Although no such simple relation is truly applicable for estimating the thermal conductivity of a complex lithology, a series conductance model for thermal conductivity is sometimes used to approximate the overall thermal conductivity (k) of a matrix:

$$\frac{1}{K} = \sum_{i=1}^n \frac{V_i}{K_i} \quad , \quad (5.a.23)$$

where K_i and V_i are the thermal conductivity and the volume fraction, respectively, of the ith component.

For the interpretation of resistivity logs, the resistivity of the conductive component of the matrix (such as shale or metallic minerals) is required.

The Pore Space Component

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. The spaces are generally interconnected and fairly regular. Porosities of this type are present in most sedimentary formations. In igneous and metamorphic

rocks, intergranular porosity is usually very low -- of the order of 1%. However, an exception is tuff in a volcanic detrital rock, that has high intergranular porosity. Fracture porosity may be naturally caused by geologic events after deposition or may be artificially generated by hydraulic or explosive fracturing to enhance formation permeability. Fracture porosity can be present in most types of formations, however, it is the dominant type of porosity 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 common in carbonate formations. Vesicular porosity is sometimes encountered in volcanic rocks, particularly basalts. This porosity is caused when the gas released from a cooling lava is either trapped as a series of gas bubbles in the matrix or leaves open channels 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% 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 which are very small; and interoolitic pores which are between the oolites. Micropores may occur in non-oolitic carbonates and in the cementing material of clastic sediments (Kieke and Hartmann, 1973).

Sonic Response to Porosity

For sonic logs, Eq. (5.a.1) can be written as:

$$\Delta t = \Delta t_f \phi_s + \Delta t_{ma} (1 - \phi_s) \quad (5.a.24)$$

or

$$\phi_s = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \quad (5.a.25)$$

where Δt = observed sonic travel time from the log,

Δt_f = sonic travel time in the fluid,

Δt_{ma} = sonic travel time in the matrix, and

ϕ_s = sonic derived porosity.

It is known that the sonic tool responds primarily to intergranular porosity (commonly called "primary" porosity) and does not "see" some types of fractured or vugular porosity (commonly called "secondary" porosity). Thus, the porosity computed from Eq. (5.a.25) will be less than a porosity as determined from the density or neutron. Due to the complex nature of acoustical wave propagation across fractures or vugs, the difference between true porosity and sonic derived porosity is not particularly equal to the theoretical amount of "secondary" porosity. The porosity difference is referred to as secondary porosity index (SPI) and is computed to give an indication of fractured or vuggy porosity (see Schlumberger, 1974 and Poupon and others, 1971).

$$SPI = \phi - \phi_s \quad (5.a.26)$$

Experience in the petroleum industry has shown the Wyllie time average equation, Eq. (5.a.2), is not valid when formations have "secondary" porosity. Conditions may exist where SPI is zero or negative (see discussion on porosity comparison, Fracture Detection and Definition, 5.c).

It should be remembered that if a nonporous rock is thoroughly fractured and rubble-like, the sonic log will respond to the porosity even though it is secondary porosity. No information is available for sonic log response in vesicular porosity. Vesicular porosity is primary porosity but has some similarity to vuggy porosity, which is secondary. It is not known to what extent the sonic log will "see" vesicular porosity.

The Fluid Component

The fluid present in the pore spaces of a geothermal reservoir is usually either steam or water or both. However, saturation of carbon dioxide (free gas) in pore spaces has been reported from the Cerro Prieto geothermal field in Mexico and suspected in the East Mesa geothermal field, California. Even when steam occurs in a geothermal reservoir, the zone of investigation of well logs may be water saturated because of condensation of steam due to well bore cooling during circulation. In a cased geothermal producing well it is possible for logs to encounter steam in the zone of investigation.

Steam and gas have practically infinite resistivity as compared to water. The resistivity of formation water depends on the salinity and temperature of the water. As far as resistivity log interpretation is concerned, the

steam and gas saturation may be considered as part of the nonconductive matrix.

For porosity logs and pulsed neutron logs, the influence of fluids in the pore space can be taken into account by substituting Eq. (5.a.3) in Eq. (5.a.1). Fluid phase does not affect gamma ray and spectral gamma ray logs. The SP log is affected by the nature of the fluid phase; however, sufficient data are lacking to quantify this effect.

The dissolved solids in the formation may affect the response of many logs and hence need to be included in some petrophysical models. For example, the quantity and type of dissolved salts in water will strongly affect the electrical resistivity of the water. Dissolved boron or lithium, each of which has a high cross section for thermal neutron capture, may substantially affect the response of a pulsed neutron log. Dissolved solids increase the bulk density and decrease the sonic travel time (Δt) of formation water; consequently, density and sonic logs respond to the amount of dissolved solids.

It should be pointed out that fluid properties are functions of temperature and, to a lesser extent, of pressure.

Hydrothermal Alteration

As mentioned before, hydrothermal alteration is a very common feature of geothermal geology. Although it affects matrix properties only, it is important enough to be discussed here separately. There are numerous possible hydrothermal alteration reactions depending on the lithologic assemblage temperature, and the chemistry of the

hydrothermal solution. It is impossible to consider all. The three most commonly encountered reactions are silicification, alteration of feldspars to clays or zeolites, and alteration of micas to chlorite.

Well log responses are usually mildly affected by silicification unless silicification reduces or alters pore structures. For example, silicification can fill in pores and fractures. Opal, a cryptocrystalline form of silica will, however, alter the responses of density and neutron logs because of its lower density (2.15 gms/cm^3) and its water content.

Alteration of feldspars to kaolinite will cause an increase in neutron response due to hydration. When potassium feldspars alter to clays, there is a resultant decrease in natural gamma ray intensity.

Alteration of biotite or muscovite mica to chlorite is accompanied by a decrease in gamma ray response due to the reduction in potassium content. It should also be accompanied by an increase in neutron porosity because of a higher hydrogen content in chlorite.

As pointed out before, it is impossible to forecast the effect of the numerous hydrothermal alteration reactions on log responses. Careful crossplotting allows diagnosis of many cases of hydrothermal alteration from well logs when used in conjunction with cores or cutting data. However, no general approach can be outlined.

Petrophysical Models for Geothermal Reservoirs

Because of the extremely diverse lithologies and pore structures encountered in geothermal reservoirs, it is

impossible to have one unique petrophysical model for all geothermal systems. We will discuss briefly some of the typical petrophysical models for geothermal log analysis.

- 1) Intergranular porosity, sedimentary clastic rock without any shale. For resistivity response, Archie's formula is adequate (Schlumberger, 1972). For porosity logs, standard response equations are applicable. This is known as a "clean sand" model and is rare in occurrence.
- 2) Intergranular porosity, shaly clastic rocks. Since shale affects the responses of many well logs, the interpretation of shaly formations is more involved than interpretation in "clean" formations. Shaliness affects log responses depending on the proportion of shale, its physical properties, and the distribution of shale in the formation. The three shale models generally accepted are the following: (a) Laminar shale -- shale exists in the form of laminae between which are layers of sand; (b) Structural shale -- shale exists as grains or nodules in the formation matrix; (c) Dispersed clay -- clay is dispersed throughout the formation, 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 information on typical shaly formation log analysis. The geothermal reservoirs in the Imperial Valley of California are of this type.
- 3) Carbonates with intergranular and fracture porosity. This model is similar to the previous ones, except that the presence of shale is usually not a problem and the degree of compaction in carbonates is quite

high and fairly uniform. When using this model, the cementation factor can be generally considered to be 2.0. Usually carbonates will be a mixture of calcite and dolomites with occasional anhydrite, pyrite, etc. A "complex lithology" interpretation technique such as described in Schlumberger (1976) may be required in such cases. Fractures may be detected by various techniques discussed in a later section.

- 4) Nonconductive, nonporous matrix with fractures. In fractured igneous and metamorphic rocks, the detection and evaluation of fractures is important in geothermal log analysis. In a later section in this report we will discuss the various techniques for locating fractures from well logs.

Diagnosis of various lithological components is the first step in the analysis of any igneous or metamorphic lithology. Comparison of core or drill cutting data with histograms and crossplots is a possible way to diagnose various lithologies. Any quantitative calculation of porosity or lithology is difficult because of the lack of knowledge of matrix properties for many "unfamiliar" minerals. However, empirical approaches based on histograms and crossplots can be sometimes used for such calculations. For an example, see Sanyal, and others (1979). The effects of heavy minerals on the density log and hydrated minerals on the neutron log should be considered.

Hydrothermal alteration is common in such rocks and it causes a different log response. Keys (1979) gave examples of the detection of hydrothermal alteration from crossplots. However, it may not always be possible to resolve the problem of hydrothermal

alteration from well logs. Detection of metamorphism from logs is even more difficult. It may be possible to use a rock strength parameter, such as $\rho_b/(\Delta t)^2$ as a crossplot variable to identify a hard metamorphic rock, such as quartzite, from its soft counterpart, sandstone.

Rock texture may affect log response in igneous and metamorphic rocks. For example, inclusions of xenoliths or flow banding or layering may affect log response. In metamorphic rocks slaty, gneissic, or schistose textures may affect log response differently. Keys (1979) observed that in the Conway granite from New Hampshire, the sonic velocity was affected by the crystal size.

- 5) Matrix with a conductive metallic mineral, such as pyrite or magnetite. Both the amount and structural arrangement of the conductive mineral in the rock will affect log responses. The effect of pyrite on log response has been discussed by Clavier and others (1976); the results are summarized in this report in the discussion on laboratory investigations. Magnetite is often present in igneous rocks and is easily detected by a magnetic susceptibility log. (Unfortunately, this is not a commonly run log.) The effect of these minerals on electrical resistivity and density logs must be considered.
- 6) Volcanic ash and tuff. Refer to the discussion on the work of Khatchikian and Lesta (1973) and Sacco (1978) in Section 1. Many geothermal reservoirs in the Snake River Plain and the Basin and Range Province are of this type.

- 7) Vuggy and oolitic carbonates. Models for vuggy carbonates are the same as other carbonates except for the consideration of secondary porosity. No model has been specifically developed for oolitic carbonates. The presence of vugs does not alter the sonic log response to the carbonate matrix.
- 8) Vesicular volcanic rocks. For an interconnected vesicular system, Archie's formula will probably be valid. It is not known to what extent the sonic log response will be affected by vesicular porosity. The other aspects of vesicular rocks are similar to those for other igneous rocks. Many geothermal reservoirs in Idaho, Nevada, and California are of this type.
- 9) Interlayered sequence of volcanic flows and tuff. This is common in many geothermal areas. Refer to Sanyal, and others (1979) for an example. These sequences often have interlayering of detrital sediments. Such geothermal reservoirs are common in the U.S. in the Snake River Plain and the Basin and Range Province.
- 10) Conglomerates/Breccias. These systems may show extreme heterogeneity in lithology. This may make it impossible to estimate lithology and porosity quantitatively, or often, even qualitatively. Fracture detection is possible as in other systems.

This discussion has presented some conceptual models based on tool responses and material balance. Quantifying the models is always difficult and sometimes impossible. The technique has been successful in some areas as described by Burke and others, (1966) where very detailed and accurate rock properties have been determined. The

application of these relationships to a complex geothermal reservoir should be approached with caution, as the following items can produce answers giving erroneous or even negative rock type volumes and incorrect porosity.

- Incorrect matrix values,
- Nonlinear tool response,
- Unknown in situ fluid type,
- "Secondary" porosity influence on sonic,
- Lack of mathematical resolution,
- Formation more complex than can be modeled for the logs available.

Examples of geothermal well log analysis from three areas are included under Section 4.

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5.b. MATRIX RESPONSE

Because of accelerated energy and mineral production efforts in the last few years, the locale of exploration and development now includes many geological settings unfamiliar to most log analysts. The log analyst of today is encountering formations composed of rocks and minerals which have not normally been found during routine log evaluation in the past. Some examples are volcanic debris in geothermal fields in Nevada and Idaho; granites in geothermal fields in New Mexico; and various sedimentary rocks with contaminants such as mica, glauconite, or pyrite in oil fields. These and many other unfamiliar lithologies provide a challenge to the log analyst and his resources.

Rocks or minerals may be identified from well samples but may not be readily detectable on well logs because the log responses of the matrix material may not be known. Often an anomaly may be noted on the logs with no hint as to the type of rock or mineral it may represent. Depending on the complexity of the lithology mixture, type of fluids, and the logs available, it may be possible to build special interpretation models for particular log analysis problems. These models will require the input of matrix characteristics for each type of rock and each type of log considered.

Many papers have been written that explain special interpretation techniques for specific log analysis

problems and rock types. These usually list the required matrix parameters which normally have been determined from log study or laboratory tests. However, in many situations, the log analyst finds it difficult or impossible to estimate the required matrix response data for unfamiliar lithologies. The following tables incorporate the gathering together of bits and pieces of matrix data from various sources in an attempt to provide the log analyst with a concise, easy-to-use reference for the matrix responses for density, sonic and neutron logs. Additional data and information can be found by consulting the technical references given as the data source.

The matrix data supplied in the tables may be applied in several ways:

- Matrix values can be input as starting points in special interpretation models.
- Certain types of rocks which are known to exist can be located within a borehole.
- Within a certain zone, the type of rocks that exist may be identified.
- When computer generated crossplots are made from well logs to determine matrix values, the data from the tables can be used as a guide. The values derived from this technique will be the most accurate for input into a special model.

Description of Data Tables

The matrix response values are classified and listed in two tables. Table 5.b.3 (for minerals) and Table 5.b.4

(for rocks) are in alphabetical order by lithology name. It is usually important to know how the chemical and structural characteristics of a special lithology relate to other minerals or rocks. Tables 5.b.1 and 5.b.2 are classification schemes for minerals and for rocks, respectively. A code number identifies the hierarchy of each mineral or rock in the classification. Only those minerals or rock types for which data are listed are included in this classification. The chemical composition is listed in Table 5.b.1 for minerals. Both tables are classified into common groups such as sulfates (for minerals) or clastics (for rocks). This allows identification of other rocks or minerals which are chemically similar. The more digits in the hierarchial code, the more specific the lithology and hence more reliable are the corresponding matrix data. A four digit code for minerals implies a single chemical species of known composition and the corresponding data can be considered the most repeatable.

TABLE 5.b.1: HIERARCHICAL RELATIONSHIP OF MINERALS

1. ORTHO- & RING SILICATES

1.1 OLIVINE GROUP

- 1.1.1 Olivine: $(\text{Mg}, \text{Fe})_2 [\text{SiO}_4]$
 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: $(\text{Mg}, \text{Fe}^{+2}) [\text{SiO}_3]$
 2.1.1.1 Enstatite/Clinoenstatite: $\text{Mg}_2\text{Si}_2\text{O}_6$
 2.1.1.2 Orthoferrosilite/Clinoferrosilite:
 $\text{Fe}_2\text{Si}_2\text{O}_6$
 2.1.2 Diopside-Hedenbergite: $\text{Ca}(\text{Mg}, \text{Fe}) [\text{Si}_2\text{O}_6]$
 2.1.3 Augite-Ferroaugite: $(\text{Ca}, \text{Na}, \text{Mg}, \text{Fe}^{+2}, \text{Mn}, \text{Fe}^{+3},$
 $\text{Al}, \text{Ti})_2 [(\text{Si}, \text{Al})_2\text{O}_6]$

2.2 AMPHIBOLE GROUP

- 2.2.1 Hornblende: $(\text{Na}, \text{K})_{0-1} \text{Ca}_2 (\text{Mg}, \text{Fe}^{+2}, \text{Fe}^{+3}, \text{Al})_5$
 $[\text{Si}_{6-7} \text{Al}_{2-1} \text{O}_{22}] (\text{OH}, \text{F})_2$

3. SHEET SILICATES

3.1 MICA GROUP

- 3.1.1 Muscovite: $\text{K}_2\text{Al}_4 [\text{Si}_6\text{Al}_2\text{O}_{20}] (\text{OH}, \text{F})_4$
 3.1.2 Glauconite: $(\text{K}, \text{Na}, \text{Ca})_{1.2-2.0} (\text{Fe}^{+3}, \text{Al}, \text{Fe}^{+2}, \text{Mg})_{4.0}$
 $[\text{Si}_{7-7.6} \text{Al}_{1-0.4} \text{O}_{20}] (\text{OH})_{4.n} (\text{H}_2\text{O})$
 3.1.3 Phlogopite: $\text{K}_2 (\text{Mg}, \text{Fe}^{+2})_6 [\text{Si}_6\text{Al}_2\text{O}_{20}] (\text{OH}, \text{F})_4$
 3.1.3.1 Eastonite: $\text{K}_2\text{Mg}_5\text{Al} [\text{Si}_5\text{Al}_3\text{O}_{20}] (\text{OH})_4$

- 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 Montmorillonite Group: $(\frac{1}{2}Ca,Na)_{0.7}(Al,Mg,Fe)_4 [(Si,Al)_8O_{20}] (OH)_4.nH_2O$

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: $NaAlSi_3O_8$
- 4.1.2.2 Oligoclase
- 4.1.2.3 Andesine
- 4.1.2.4 Labradorite
- 4.1.2.5 Bytownite
- 4.1.2.6 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: $\text{SiO}_2 \cdot n\text{H}_2\text{O}$
 - 4.2.1.3 Chert: SiO_2
 - 4.2.1.4 Flint: SiO_2

4.3 ZEOLITE GROUP

- 4.3.1 Zeolites: $(\text{Na}_2, \text{K}_2, \text{Ca}, \text{Ba}) [\text{Al}, \text{Si}] \text{O}_2]_n \cdot x\text{H}_2\text{O}$

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: $\text{Fe}^{+2}\text{Fe}_2^{+3}\text{O}_4$

5.2 HYDROXIDES

- 5.2.1 Limonite: $2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$

5.3 SULFIDES

- 5.3.1 Pyrite: FeS_2
- 5.3.2 Pyrrhotite: $\text{Fe}_n\text{S}_{n+1}$
- 5.3.3 Galena: PbS
- 5.3.4 Chalcopyrite: CuFeS_2
- 5.3.5 Marcasite: FeS_2
- 5.3.6 Sphalerite: ZnS

5.4 SULFATES

- 5.4.1 Barite: BaSO_4
- 5.4.2 Celestite: SrSO_4
- 5.4.3 Gypsum: $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
- 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: $Ca_3(PO_4)_2 \cdot H_2O$
- 5.6.2 Dahllite: $Ca_5(PO_3)_3 \cdot X(CO_3OH)_X \cdot OH$

5.7 BORATES

- 5.7.1 Kernite: $Na_2B_4O_6(OH)_2 \cdot 3H_2O$

5.8 HALIDES

- 5.8.1 Halite (Salt): $NaCl$
- 5.8.2 Sylvite: KCl
- 5.8.3 Carnallite: $KCl \cdot MgCl_2 \cdot 6H_2O$
- 5.8.4 Tachydrite: $CaCl_2 (MgCl_2)_2 (H_2O)_{12}$

5.9 NATIVE ELEMENTS

- 5.9.1 Sulfur: S_8
- 5.9.2 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
- 1.1.5 Conglomerate

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

2.2 DIORITE-ANDESITE FAMILY

- 2.2.1 Plutonic Class
 - 2.2.1.1 Diorite
- 2.2.2 Volcanic Class
 - 2.2.2.1 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)

3.1 FOLIATED

- 3.1.1 Slate
- 3.1.2 Phyllite
- 3.1.3 Schist
- 3.1.4 Gneiss

3.2 NON-FOLIATED

- 3.2.1 Meta-Conglomerate
- 3.2.2 Quartzite
- 3.2.3 Marble
 - 3.2.3.1 Calcite Marble
 - 3.2.3.2 Dolomite Marble

Fig. 5.b.1. Order of crystallization of the common rock forming minerals.

Fig. 5.b.2 Classification of Metamorphic Rocks.

1. Foliated

TEXTURE			COMPOSITION					ROCK NAME		
ORIENTED GRAINS	Non-layered	Very fine grained	CHLORITE	MICA	QUARTZ				SLATE	1.1
		Fine grained							PHYLLITE	1.2
		Coarse grained							SCHIST	1.3
	Layered	Coarse grained				FELDSPAR	AMPHIBOLE	PYROXENE	GNEISS	1.4

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

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

General Comments

A short, abbreviated guide to row and column definition is located on page 1 of Table 5.b.3.

References have been assigned a letter rather than listed in alphabetical order for simplification of the computer listing.

All entries of matrix data listed in Tables 5.b.3 and 5.b.4 are accompanied by a letter identifying the reference source. A number and hyphen immediately preceding this reference will indicate the number of samples within the listed range of values, or the number of samples used to determine the arithmetic average.

Columnar Data

The data in Tables 5.b.3 and 5.b.4 are identified and listed in seven columns.

Column 1: Rock or Mineral name and classification code (as listed in Tables 5.b.1 and 5.b.2).

Column 2: Data associated with density logs.

Column 3: Data associated with acoustic or sonic logs.

Column 4: Data associated with neutron logs.

Column 5: Additional radioactive parameters.

Column 6: Miscellaneous formation parameters.

Column 7: Row number identification.

Row Data

Columns 2 to 6 are further detailed by up to 5 rows of data.

Density Data, Column 2

- Row 1: Specific Gravity.
- Row 2: Range of Specific Gravity.
- Row 3: Apparent matrix density based on a tool calibration with Z/A ratio of 0.5 (g/cm³).
- Row 4: Actual log reading of rock or mineral (g/cm³).
- Row 5: Apparent matrix value as determined by charts or crossplots. Method used noted with reference (g/cm³).

Sonic data, Column 3

- Row 1: Average compressional matrix travel time (microsec/m).
- Row 2: Range of compressional matrix travel time (microsec/m).
- Row 3: Average shear matrix travel time (microsec/m).
- Row 4: Actual log reading of rock or mineral (microsec/m).
- Row 5: Apparent matrix value as determined by charts or crossplots (microsec/m). Method used noted with reference.

Note: Laboratory measurements of sonic data may have been made at Standard Temperature and Pressure

or at simulated in situ conditions. The difference may be significant. When using the sonic matrix data, refer to the individual reference for the conditions of measurement so a quality judgment may be made for your particular application.

An example of pressure and temperature effects is shown in Fig. 5.b.3 where sonic values are plotted versus temperature for several different pressures. The change in sonic travel time (compressional) for this particular sample of granite is greatest between 200 and 500 bars. The dashed line is an estimated temperature-pressure profile assuming a geothermal gradient of $18.2^{\circ}\text{C}/\text{km}$ ($1.0^{\circ}\text{F}/100\text{ ft}$) and a lithostatic gradient of $226\text{ bar}/\text{km}$ ($1.0\text{ psi}/\text{ft}$). This illustrates the possible changes which would occur when drilling an "average" well. Additional information on this subject can be found by consulting references R and V.

Neutron data, column 4

- Rows 1, 2 and 3: Neutron matrix value or a range of values (Percentage units, Limestone scale).
- Row 4: Actual log reading of rock or mineral (Percentage units, Limestone scale).
- Row 5: Apparent matrix value as determined by charts or crossplots (Percentage units, Limestone scale). Method used noted with reference.

Note: The response of a neutron tool is influenced by many design factors. Some of these are: detector type and shielding; source-detector spacing; source type and energy; and surface equipment processing. For the most part, neutron tools may be grouped in three classes.

- A. Single detector: large hole size effect - moderate matrix effect.
- B. Dual detector: mud cake compensated - small hole size effect - greatest matrix effect.
- C. Single detector, pad type: mud cake effect - 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 technique used. When a particular commercial tool is listed, the response is given in limestone units.

Additional Radioactive Parameters, column 5

- Row 1: Potassium content - (% K by volume).
- Row 2: Uranium content - (ppm U).
- Row 3: Thorium content - (ppm Th).
- Row 4: Total natural gamma ray response - (API units).
- Row 5: Sigma (Σ) - pulsed neutron response (c.u. - capture units.)

Miscellaneous formation parameters, column 6

Row 1: Thermal Conductivity - $10^{-3}(\text{cal/cm}^2\text{-sec})/(\text{°C/cm})$. If specified, the temperature is listed.

Row 2: Electrical Resistivity ($\text{ohm-m}^2/\text{m}$).

NOTE: $1.E + 05 = 1 \times 10^5$
 $1.E - 02 = 1 \times 10^{-2}$

Fig. 5.b.3. Variation of elastic wave with pressure and temperature.

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MATRIX VALUES FOR DENSITY - SONIC - NEUTRON AND OTHER FORMATION PARAMETERS
TABLE 5.B.3 PAGE 1

QUICK ROW GUIDE - TABLE 5.B.3, PAGE 1

MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
QUICK GUIDE FOR ROWS						
COLUMN 1 *****	COLUMN 2 *****	COLUMN 3 *****	COLUMN 4 *****	COLUMN 5 *****	COLUMN 6 *****	
ROCK OR MINERAL NAME	SPECIFIC GRAVITY	TT-COMPRESSIONAL	NEUTRON VALUE	GAMMA RAY - K-%	THERMAL CONDUCT	1
ROCK OR MINERAL CODE	S.G. - RANGE	T.T. - RANGE	NEUTRON VALUE	GAMMA RAY- U-PPM	ELECTRICAL RESIS	2
	APPARENT DENSITY	T.T. - SHEAR	NEUTRON VALUE	GAMMA RAY-TH-PPM		3
	LOG READING	LOG READING	LOG READING	GAMMA RAY - API		4
	DERIVED VALUE	DERIVED VALUE	DERIVED VALUE	SIGMA		5
ALBITE 4.1.2.1	2.62 B 2.61-2.65 B 2.56 B	164.7 B 162.4-166.0 B	- .5 L	6.77 B 7.6 X		1 2 3 5 5
		180.8 H				1
	2.62 N 2.61-2.63 2-N	161.4 N 137.8-228.4 11-N 278.9 9-N				1 2 3
	2.63 P	154.9 P 148.6-160.4 3-P 320.6 3-P				1 2 3
	2.62 Z 2.59 Z		-1 -1	Z AA		1 3
				7.47 Z		5

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MATRIX VALUES FOR DENSITY - SONIC - NEUTRON AND OTHER FORMATION PARAMETERS
TABLE 5.B.3 PAGE 2

QUICK ROW GUIDE - TABLE 5.B.3, PAGE 1

MINERAL AND CODE	DENSITY		SONIC		NEUTRON		ADDL RADIOACTIVE		MISC.		R O W
ANDESINE 4.1.2.3	2.676 2.65	Z Z			-1. -2.	Z AA	7.378	Z			1 3 5
ANHYPDRITE 5.4.4	2.89-2.98 2.977	A C	164.0	C	0	T	0	C	7-13.4 1.E+04 / 1.E+10 B	B	1 2 3 5 5
	2.928	N	170.0 157.8-208.3	N 4-N			12.1 13	W X			1 2
	2.96 2.98	Z Z			-1. -2.	Z AA	12.45 12.30	Z B			1 3 5 5
ANORTHITE 4.1.2.6	2.76 2.60	A E	149.0	B	-1.2	L	7.4	X			1 3 5
	2.76 2.74	Z Z			-1 -2	Z AA	7.24	Z			1 3 5
ARAGONITE 5.5.4	2.917	N	175.5	N			8.12	B			1 5
	2.94	L			.7	L					1

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MATRIX VALUES FOR DENSITY - SONIC - NEUTRON AND OTHER FORMATION PARAMETERS
TABLE 5.8.3 PAGE 3

QUICK ROW GUIDE - TABLE 5.8.3. PAGE 1

MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
AUGITE 2.1.3	3.26 3.2 -3.4 3.23	N A E	267.7 188.7-338.9 367.8	N 3-N 2-N	0.3- 1 L 84.8-90.1 AC	1 2 3 5
BARITE 5.4.1	4.45 4.3 -4.6 3.96 4.48 4.09	B B B Z Z			19.40 B -1. -2. Z AA 6.77 Z	1 2 3 5 1 3 5
BIOTITE 3.1.4	2.9 2.65-3.1 2.84	B B B	166.7 128.3-237.5 735.3	N 2-N 2-N	6.0 B 6.7-8.3 Y LT 0.01 Y 25.20 B 35 +- 10 X	1 2 3 5 5
	2.93	U	196.9	U	13 -16 U	1 3
WET-SEE REFERENCE	3.08-2.95 3.06-2.93	Z Z		8. -14. 16.- 26.0	Z AA	2 3
				94-104 29.63-30.04	Z Z	4 5
DRY-SEE REFERENCE	3.12-3.00 3.10-2.97	Z Z		6. -12. 13.- 23.0	Z AA	2 3
				95-105 29.77-30.22	Z Z	4 5

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MATRIX VALUES FOR DENSITY - SONIC - NEUTRON AND OTHER FORMATION PARAMETERS
TABLE 5.B.3 PAGE 4

QUICK ROW GUIDE - TABLE 5.B.3, PAGE 1

MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
BYTOWNITE 4.1.2.5	2.71 2.732 2.71	N Z Z	144.4 135.8-149.6 288.1 N 3-N 3-N	-1. -2. Z AA 7.286 Z		1 2 3 1 3 5
CALCITE 5.5.1	2.71 2.71 2.70 2.71 2.71	A C N Z Z	155.8 161.4 140.4-208.3 259.5 N 5-N 2-N	0 0. -1. Z AA 7.08 Z	LT .1 LT 1.0 LT 0.5 7.48 7.3 Y Y Y B X 5-13 1.E+07 / 1.E+12 B	1 2 3 5 5 1 2 3 1 3 5
CARNALLITE 5.8.3	1.61 1.57	C C	255.9 273.3 C B	65 370.92 200 370 C X B		1 3 4 5 1 5

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MATRIX VALUES FOR DENSITY - SONIC - NEUTRON AND OTHER FORMATION PARAMETERS
TABLE 5.B.3 PAGE 5

QUICK ROW GUIDE - TABLE 5.B.3, PAGE 1

MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
CARNALLITE (CONT.)	1.61 1.57	Z Z	41. 60+	Z AA 204 368.99	Z	1 3 4 5
CELESTITE 5.4.2	3.95-3.97 3.71 3.97 3.79	A E Z Z	-0.5 -1. -1.	L Z AA 7.90	Z	1 2 3 1 3 5
CHALCOPYRITE 5.3.4	4.2 4.07	Z Z	-2. -3.	Z AA 102.13 80.95	Z B	1 2 3 5 5
CHLORITE 3.2.1	2.71 2.60-3.22 2.74	B B B	32 26 -54	B 17.56 25 +- 15 L	12.5 B X	1 2 3 5 5 1

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MATRIX VALUES FOR DENSITY - SONIC - NEUTRON AND OTHER FORMATION PARAMETERS
TABLE 5.B.3 PAGE 6

QUICK ROW GUIDE - TABLE 5.B.3, PAGE 1

MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
CHLORITE (CONT.) WET-SEE REFERENCE	2.77 2.76	Z Z	37 52	7 AA 1 24.87	Z Z	1 3 4 5
DRY-SEE REFERENCE	2.79 2.79	Z Z	36. 51.	Z AA 1 24.91	Z Z	1 3 4 5
COAL. ANTHRACITE 5.10.3	1.60 1.32-1.80 1.64	B B B	344.5 295.3-393.7	B 40 B 1.08 22	1.E-03 / 5. B	1 2 3 5 5
	1.51 1.47	Z Z	37. 38.	Z AA 8.65	Z	1 3 5
COAL. BITUMINOUS 5.10.2	1.35 1.15-1.7 1.4	B B B	393.7 328.1-459.3	B 66 B 1.54 35	1.E+01 / 1.E+06 B	1 2 3 5 5
	1.27 1.24	Z Z	50+ 60+	Z AA 14.30	Z	1 3 5

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MATRIX VALUES FOR DENSITY - SONIC - NEUTRON AND OTHER FORMATION PARAMETERS
TABLE 5.8.3 PAGE 7

QUICK ROW GUIDE - TABLE 5.8.3, PAGE 1

MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
COPROLITE 3.	2.4 - 2.65 Q	164.0 Q	0 Q			1
DIOPSIDE 2.1.2	3.2 A 3.08 N 3.07 E	180.1 N 269.4 3-N		23.8 AC		1 3 5
DOLOMITE 5.5.3	2.85 A 2.876 C 2.784 N 2.58-2.83 5-N 2.87 Z 2.88 Z	142.7 C 191.3 N 165.0-219.2 4-N 305.5 3-N	4 2. 1. Z AA	T 0.1 - 0.3 Y 1.5-10 Y LT 2.0 Y 4.8 X 4.70 Z 4.78 B	9.3-11.9 B 1 / 7.E+03 B	1 2 3 5 2 3 5
FAYALITE 1.1.1.2	4.39 A 4.22 E		2.0 L		68.2 AC	1 3 5

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MATRIX VALUES FOR DENSITY - SONIC - NEUTRON AND OTHER FORMATION PARAMETERS
TABLE 5.8.3 PAGE 8

QUICK ROW GUIDE - TABLE 5.8.3, PAGE 1

MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
FORSTERITE 1.1.1.1	3.2 3.19	A E	1.6	L 3.9 AC		1 3 5
GALENA	7.5 6.39	Z Z	323.5 254.3-531.9 4-N -3. -3.	Z AA 13.36 12.47 Z B	1.E-02 / 1.E-05	1 2 3 5 5
GLAUCONITE, 3.1.2	2.30 2.20-2.80 2.30	B B B	19	B 5.08-5.30 Y 16.80 25 +- 5 B X		1 2 3 5 5
WET-SEE REFERENCE	2.55-2.80 2.51-2.65 2.49-2.63	L Z Z	31 -40 26.- 21.0 42.- 37.	L Z AA 70-88 22.37-26.70 Z Z		1 2 3 4 5
DRY-SEE REF	2.69-2.80 2.67-2.77	Z Z	18.- 16. 33.- 30.	Z AA 73-91 22.39-27.09 Z Z		2 3 4 5

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MATRIX VALUES FOR DENSITY - SONIC - NEUTRON AND OTHER FORMATION PARAMETERS
TABLE 5.8.3 PAGE 9

QUICK ROW GUIDE - TABLE 5.8.3, PAGE 1

MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
GRAPHITE 5.9.2	2.16 N 327.1 303.2-341.2 537.8 2.23 2.04-2.23 2.23 A B 2.25 L	N 3-N 3-N	9.5 L	0.38 B	1.E-04 / 1.E-06	1 2 3 1 2 3 5 3
GYPSUM 5.4.3	2.32 2.351 A C 2.32 2.35 Z Z	172.3 C	49 C 50+ 60+ Z AA	T 0 18 19 C W X 18.5 19.40 Z B		1 3 4 5 5 1 3 5 5
HALITE 5.8.1	2.16 2.03 C C	219.8 C	0 C	0 C 760 770 C W X	14.3 (8-15) 1.E+04 / 1.E+14 B B	1 2 3 4 5 5

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MATRIX VALUES FOR DENSITY - SONIC - NEUTRON AND OTHER FORMATION PARAMETERS
TABLE 5.B.3 PAGE 10

QUICK ROW GUIDE - TABLE 5.B.3, PAGE 1

MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
HALITE (CONT.)	2.17 2.04	Z Z	-2. -3.	Z AA 754.2 752.36	Z B	1 3 5 5
HEMATITE 5.1.1	5.26 4.9 -5.3 5.04 5.21 4.93-5.5 4.93 5.27 5.18	B B B N 2-N P Z Z	140.8 H 145.0 140.8-151.9 260.2 N 4-N 3-N 146.7 142.1-151.9 260.5 P 3-P 3-P 4. 11.	L Z AA 101.37	25 1.4E-03/ 1.E+06 100.47 104 B X Z	1 2 3 5 1 2 3 1 2 3 1 3 5
HORNBLENDE 2.2.1	3.27 3.12-3.32 3.2 3.2	N 4-N Z Z	143.7 123.0-163.7 267.4 N 15-N 15-N	 4. 8. Z AA	 18.12 Z	1 2 3 1 3 5

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MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
HORNLENDE (CONT.)	3.32	P 157.2 139.4-170.9 300.2	P 3-P 3-P			1 2 3
ILLITE 3.3.2	2.84 2.6 -3.0 2.81	B B B	37	B 4.5 1.5 39.90	Y Y B	1 2 3 5
	2.58-2.65	L	20 -30	L		1 2
WET-SEE REFERENCE	2.53 2.52	Z Z	20. 30.	Z AA		1 3 4
				67 17.58	Z Z	5
DRY-SEE REFERENCE	2.65 2.63	Z Z	15. 24.	Z AA		1 3 4 5
				69 17.22	Z	
ILMENITE 5.1.2	4.75 4.5 -5.0 4.52	B B B	6.5	L	1.E-02 / 1.E+02	1 2 3 5
				158.23	B	

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MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
KAINITE 5.4.7	2.13 2.12 2.13 2.12	C C Z Z	45 40. 60+	C Z AA 227 195.14 196.13	C Z Z B	1 3 4 1 3 4 5 5
KAOLINITE 3.3.1	2.63 2.4 -2.68 2.68	B B B	37 51	B L	0.42 1.5 - 3 6 - 19 13.06 Y Y Y B	1 2 3 5 1
WET-SEE REFERENCE	2.42 2.41	Z Z	34 37	Z AA	6 14.12 Z Z	1 3 4 5
DRY-SEE REFERENCE	2.44 2.44	Z Z	33. 36.	Z AA	6 13.98 Z Z	1 3 4 5
KERNITE 5.7.1	1.91 1.92	B B	164.0 B	50 B	12793.7 B	1 3 5

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MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
KIESERITE 5.4.8	2.57 2.43 2.57 2.59	A E Z Z	31 38. 43.	B Z AA 13.96 12.77	 Z B	1 3 1 3 5 5
LABRADORITE 4.1.2.4	2.683 2.704 2.68	N Z Z	142.1 125.0-165.0 18-N 268.1 18-N	 -1. -2. Z AA 7.332	 Z	1 2 3 1 3 5
LANGBEINITE 5.4.5	2.83 2.81 2.83 2.82	B E Z Z	170.6 -1. -2.	B 0 Z AA 275 78.87 271 24.19	C C B Z Z	1 3 4 5 1 3 4 5

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MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
LIGNITE 5.10.1	1.1 0.5 -1.5 1.23 1.19	B B Z Z	525.0 459.3-590.6 47. 52.	B B Z AA 12.79	.33-1 / 68F 4.E+03 Z	1 2 5 1 3 5
LIMONITE 5.2.1	3.8 3.51-4.0 3.72 3.55 3.5 3.59	B B B N Z Z	186.7 184.4-189.3 336.6 50+ 60+	55 B Z AA 71.12	1.E+06 / 1.E+08 B 74.10 80 X Z	1 2 3 5 1 1 3 5
MAGNETITE 5.1.3.1	4.73 4.53-4.86 4.52 4.81	N 6-N E P	244.8 169.6-434.7 239.2 230.3-245.7 507.6	N 6-N P 3-P 3-P	30 1.E-02 / 1.E-04 B 107 X	1 2 3 5 1 2 3

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MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
MAGNETITE (CONT.)	5.18 4.97-5.18 4.95	B B B		112.10 B		1 2 3 5
	5.18 5.08	Z Z	3. 9.	Z AA 103.08 Z		1 3 5
MARCASITE 5.3.5	4.89 4.87	Z Z	-2. -3.	Z AA 88.12 Z		1 3 5
MONTMORILLONITE 3.3.3	2.35 2 -3 2.35	B B B	17	B 0.16 2.5 14 - 24 8.10 Y Y Y B		1 2 3 5
WET-SEE REFERENCE	2.12 2.12	Z Z	40. 44.	Z AA 3 14.12 Z Z		1 3 4 5
DRY-SEE REFERENCE	2.53 2.52	Z Z	20. 24.	Z AA 3 11.23 Z Z		1 3 4 5

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MINERAL AND CODE	DENSITY		SONIC		NEUTRON		ADDL RADIOACTIVE		MISC.	R O W
MUSCOVITE 3.1.1	2.93	B	160.4	N	13.0	B	7.9-9.8	Y	1.E+11 / 1.E+12 B	1
	2.76-3.1	B	124.7-225.1	2-N						2
	2.91	B	488.9	2-N			LT 0.01	Y		3
							17.30	B	5	
	2.83	L			14.5	6			1	
	2.79	N							1	
	2.77	E							3	
			210.0	U	20	U			1	
	2.82	U							3	
	2.82	Z			12	Z			1	
2.82	Z			20	AA	16.85	Z	3		
								5		
NAHCOLITE 5.5.6	2.20	B			24	B				1
	2.16	B								3
OLIGOCLASE 4.1.2.2	2.64	N	158.1	N						1
			116.8-182.4	18-N						2
			279.5	18-N						3
	2.648	Z			-1.	Z				1
	2.62	Z			-2.	AA	7.424	Z		3
									5	

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MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
OLIVINE 1.1.1	3.32 3.27-4.37	N A 114.2 101.4-129.3 216.9	N 3-N 3-N 1.6- 2	L 31.74 B		1 2 3 5
OPAL 4.2.1.2	2.0 -2.25 2.15 2.16-2.04 2.13-2.01	A D Z Z 190.3 190.0	H N 8 4. -11. 2. -11. 5 -13	D Z AA L 5.03 - 7.05 Z		1 2 3 2 3 5 1
ORTHOCLASE 4.1.1.1	2.57 2.55-2.63 2.55 2.55 2.52	B B B Z Z 226.7 227.0 174.9-263.1	H N 3-N -1.8 -2 -3	L Z AA 11.8 - 14 LT .01 16.00 15 204 15.51	Y Y B X Z Z	1 2 3 5 5 1 2 3 4 5

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MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
PHLOGOPITE 3.1.3	2.81 2.86	N A 163.4 125.7-233.6 680.2 2-N 2-N				1 2 3 1 5
				33.3 AC		
POLYHALITE 5.4.6	2.78 2.79	B B	188.7 B	17 B	3.7 B	1 3 4 5
	2.78 2.79	Z Z	15 14. 25.	C Z AA		1 1 3 4 5
				188 23.70 Z Z		
PYRITE 5.3.1	4.88 4.81-5.02 4.74	N 7-N E	128.6 114.8-138.5 203.8 N 12-N 7-N	-6.7 L	25 - 40 1.E-01 / 1.E-04 B B	1 2 3 5 5
	4.81	P	129.9 128.9-130.9 209.3 P 3-P 3-P			1 2 3
	5.06	B				1
	4.91	B	213.3-226.3 AD			2 3 5
				89.06 B		

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MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADOL RADIOACTIVE	MISC.	R O W
PYRITE (CONT.)	5.0 4.99	Z Z	-2. -3.	Z AA 90.10	Z	1 3 5
PYRRHOTITE 5.3.2	4.55 4.58-4.65 4.40	N A B	213.3 212.3-214.6 362.9	N 3-N 3-N -7. L	1.E-04 / 1.E-05 B	1 2 3 5
	4.55 4.6 4.53	P Z Z	213.3	P -2. -3. Z AA	94.18	1 3 5
QUARTZ 4.2.1.1	2.65 2.648	A C	169.0	C -4 T	1.E-12 / 1.E-14 B	1 2 3
SERPENTINE 3.2.3	2.3-2.6 2.694 2.50-2.89 2.66	A N 18-N E	178.5 141.7-299.6 297.3	N 17-N 2-N	4.3 - 5.9 9.2-10.4	1 2 3 5

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MINERAL AND CODE	DENSITY		SONIC		NEUTRON		ADDL RADIOACTIVE		MISC.	R O W		
SIDERITE 5.5.2	3.8	A			4.5	L			1.E+01 / 1.E+03 B	1		
	3.67	E					52	X		2		
										3		
	3.94	Z			5.	Z			1			
	3.89	Z			12.	AA	52.31 68.81	Z B	3 5 5			
SPHALERITE 5.3.6	4.0	Z			-3.	Z			1.E+05 / 1.E+07 B	1		
					-3.	AA				2		
	3.85	Z			-3.	AA	25.34 38.33	Z B		3 5 5		
	SULFUR 5.9.1	2.05-2.09	A	400.3	C	0	S			.65 / 68F	B	1
		2.03	C							1.E+09 / 1.E+16 B	B	2
											3	
2.07		Z			-2.	Z					1	
2.02		Z			-3.	AA	20.22 19.06	Z B			3 5 5	

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MINERAL AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
SYLVITE 5.8.2	1.984	C	242.8	C		1
	1.863	C			1.E+14 / 1.E+15 B	2
				500	C	3
				580	X	4
	1.98	Z	-2.	Z		5
	1.86	Z	-3.	AA		1
TACHYDRITE 5.8.4						3
	1.68	Z	50+	Z		5
	1.66	Z	60+	AA		3
				406.02		5
TRONA 5.5.5	2.125	B	213.3	B		1
	2.11-2.15	B				2
	2.14	B				3
				0	C	4
				16.21	B	5
	2.12	C	40	C		1
	2.10	C				3
	2.12	Z	24.	Z		1
	2.08	Z	35.	AA		3
				15.92	Z	5

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ROCK AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
ANDESITE 2.2.2.1	2.68	P 184.7 184.1-185.0 3-P 300.2 3-P				1 2 3
	2.70	P 176.5 175.2-177.8 3-P 310.7 3-P				1 2 3
	2.67 2.62-2.70	N 184.7 3-N 176.5-191.3 4-N 323.2 3-N				1 2 3
ANDESITE BRECCIA 2.2.2.1	2.73	P 210.0 199.2-216.5 3-P 315.3 3-P				1 2 3
	2.73	N 210.0 315.3 N				1 3
ANDESITE, HORNBLENDE 2.2.2.1	2.32	P 376.0 369.1-400.0 3-P 578.1 3-P				1 2 3
ANDESITE, VESICULAR 2.3.3.1	2.57	P 183.1 178.8-188.0 3-P 188.0 3-P				1 2 3

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TABLE 5.B.4 PAGE 2

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ROCK AND CODE	DENSITY		SONIC		NEUTRON		ADDL RADIOACTIVE		MISC.	R O W
ANORTHOSITE 2.3.1.5	2.74 2.68-2.81	N 8-N	155.8 148.6-175.5 276.6	N 6-N 3-N						1 2 3
			149.0	B						1
	2.75	P	148.6 147.0-151.6 271.0	P 3-P 3-P						1 2 3
BASALT 2.3.2.1	2.55 2.0-3.0 3.03	N 21-N G	200.5 154.2-334.3 363.9	N 20-N 19-N			0.61 - 1.7 0.99 - 1.7 1.96 - 6.8	Y Y Y	4 - 7 8.E+02 / 1.E+05 B	1 2 3
			177.2	G	7	6				1
	2.97	P	154.2 279.2	P 3-P						1 3
	2.69	P	186.4 184.7-188.0 325.8	P 3-P 3-P						1 2 3
	2.73	P	179.8 179.1-180.5 338.9	P 3-P 3-P						1 2 3

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ROCK AND CODE	DENSITY		SONIC		NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
BASALT, OLIVINE 2.3.2.1	3.00	P	169.0	P				1
			168.6-169.3	3-P				2
			281.8	3-P				3
	2.83	P	174.2	P				1
			171.6-176.5	3-P				2
			295.0	3-P				3
CONGLOMERATE - BRECCIA MOZAIC IN GRANITE MATRIX - TIGHTLY CLOSED FRACTURES 2.1.1.1 / 1.1.5	2.75	I	187.7	I				1
	2.78	I	191.6	I				1
DIABASE 2.3.1.3	2.98	B	146.3	B		LT 1.0	Y	1
	2.96-3.05	6-B	144.4-150.9	B		LT 1.0	Y	2
	2.95	B				2.4	Y	3
						17.12	6-B	5
			143.7	M				1
	2.998	N	156.5	N				1
			127.6-194.2	15-N				2
			281.5	10-N				3
	2.97	P	167.7	P				1
			166.7-169.6	3-P				2
			295.9	3-P				3

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ROCK AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
DIORITE 2.2.1.1	2.97 2.91-3.02 2.91	N 2-N P 187.3 180.5-196.2 308.7	N N P 3-P 3-P	1.1 2.0 8.5 14.33 13-B	Y Y Y 10	1 2 3 5 1 2 3
DIORITE, QUARTZ 2.2.1.1	2.88 2.80-2.93	N 3-N	188.7 181.8-196.2 295.0	N 2-N N		1 2 3
DUNITE 2.3.1.4	3.3 3.24-3.74 3.29 3.30 2.96-3.76 3.25	B 4-B B N 34-N P	125.3 113.9-134.8 124.3 138.5 120.4-183.1 252.3 157.5 150.3-170.0 271.0	B B M N 29-N 9-N P 3-P 3-P	LT 0.02 LT 0.01 LT 0.01 3.3 4-B	1 2 3 5 1 2 3 1 2 3

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ROCK AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
GABBRO 2.3.1.1	2.976 B 2.85-3.12 27-B 2.94 B	139.1 B 138.5-156.2 B		0.46 - 0.58 Y .84-0.9 Y 2.7 - 3.85 Y 21.47 27-B	8.E+02 / 1.E+05 B	1 2 3 5
		143.4 M				1
	2.95 N 2.8 -3.05 9-N	156.2 N 145.3-172.6 5-N 295.6 4-N				1 2 3
GABBRO WITH FRACTURES 2.3.1.1	3.00 I	153.2 I 294.6 I				1 3
GABBRO, QUARTZ 2.3.1.1	2.99 N	154.9 N 285.8 N				1 3
GABBRO, GRANODIORITE FRACTURED 2.3.1.1/2.1.1.2	2.89 I	155.2 I 300.9 I				1 3

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ROCK AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
GNEISS 3.1.4	2.73 2.64-2.91	N 22-N	177.8 127.0-344.8 397.3		1.E+02 / 1.E+04 B	1 2 3
GNEISS, DARK AND POORLY BANDED 3.1.4	3.04	I	179.5 330.7			1 3
GNEISS, GRANITIC, PINK TO GRAY 3.1.4	2.75	I	159.5 324.8			1 3
GNEISS, GRAY, LIGHT TO MEDIUM 3.1.4	2.80	I	158.5 309.4			1 3
GNEISS, GRAY TO GREENISH-GRAY 3.1.4	2.83	I	149.3 317.3			1 3

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ROCK AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
GRANITE 2.1.1.1	2.667 B 2.52-2.81 155-B 2.65 B	166.7 B 153.6-175.5 B		2 - 6 Y 3.2 - 16 Y 14 - 62 Y 11.62 155-B	5 - 8.4 B 7.7-7.89 AB	1 2 3 5 1 2
	2.68 N 2.45-2.94 63-N	212.9 M 175.5-250.3 M 184.4 N 139.8-270.4 67-N 342.2 47-N				1 2 3
GRANITE, GRAY TO PINK 2.1.1.1	2.88 I	139.8 I 271.3 I				1 3
GRANITE, MED GRND, QTZ FILLED FRACTURES 2.1.1.1	2.62 I	180.8 I 437.7 I				1
GRANODIORITE 2.1.1.2	2.63 N	227.4 N 318.6 N		2 - 5.5 Y 2 - 2.6 Y 9.3 - 12.1 Y 11.33 11-B		1 2 3 5
GREYWACKE 1.1.4	2.705 N	173.6 N 161.4-185.0 4-N 266.4 2-N				1 2 3

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ROCK AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
MARBLE 3.2.3	2.736 2.58-2.93 2.71	N 64-N P 187.3 183.4-192.9 353.4	N 63-N 59-N P 3-P 3-P			1 2 3 1 2 3
MARBLE, DOLOMITE 3.2.3.2	2.825 2.825	J J	142.7 142.7	0 J		4 5
MARBLE, CALCITE 3.2.3.1	2.77 2.77	J J	163.4 162.4	0 J		4 5
MONZONITE, QUARTZ 2.1.1.4	2.64 2.63-2.65	N 4-N	185.4 171.9-196.2 315.3	N 3-N 3-N		1 2 3
NORITE 2.3.1.2	2.984 2.72-3.02 2.97 2.96 2.85-3.08	B 11-B B N 8-N	144.7 142.7-160.8 154.9 151.6-161.8 294.6	B B N 5-N 4-N	6.42 	B 1 2 3 1 2 3

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ROCK AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
OBSIDIAN 2.1.2.2	2.35 P 2.35 P 2.39 2.35-2.44 3-N	171.9 P 170.9-172.3 3-P 280.2 3-P 170.9 P 172.3 N 171.9-172.3 2-N 281.8 2-N				1 2 3 1 1 2 3 5
			12.88 11-B			
PHYLLITE 3.1.2	2.79 J 2.89	191.9 J 155.8	8 J			4 5
QUARTZITE 3.2.2	2.60 N 2.54-2.72 8-N 2.70 J 2.68	180.8 N 151.6-303.2 14-N 332.0 8-N 175.5 J 178.8	-1.5 J		16.05 8	1 2 3 4 5
RHYOLITE 2.1.2.1	2.39 P 2.05 P	243.8 P 237.5-247.4 3-P 406.5 3-P 305.8 P 288.1-316.6 3-P 504.9 3-P		4.2 5 Y Y		1 2 3 1 2 3

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QUICK ROW GUIDE - TABLE 5.8.3, PAGE 1

ROCK AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
RHYOLITE (CONT.)	2.258	N 239.2 143.1-316.6 3-N 431.1 5-N				1 2 3
SHIST, MICA 3.1.3	2.79 2.83	K 196.9 162.4	6.5 K			4 5
TUFF 1.3.2	1.38	P 699.2 662.1-735.3 3-P 1149. 3-P		2.04 Y 5.96 Y 1.56 Y		1 2 3
TUFF, ASH-FLOW 1.3.2	2.69	I 206.0				1
TUFF, DEVITRIFIED TO ARGILLIZED, PARTIALLY TO DENSELY WELDED 1.3.2 1.3.2	2.56	I 196.2 481.7				1 3
VOLCANIC BRECCIA 1.3	2.19	P 236.9 236.9 N 401.6 N				1 1 3

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MATRIX VALUES FOR DENSITY - SONIC - NEUTRON AND OTHER FORMATION PARAMETERS
TABLE 5.8.4 PAGE 11

QUICK ROW GUIDE - TABLE 5.8.3, PAGE 1

ROCK AND CODE	DENSITY	SONIC	NEUTRON	ADDL RADIOACTIVE	MISC.	R O W
TUFF, ZEOLITIZED BEDDED 1.3.2	2.58	1 208.3 524.0	1 1			1 3

REFERENCES FOR MATRIX PARAMETERS

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- C. M. P. Tixier and R. P. Alger, "Log Evaluation of Non-metallic Mineral Deposits," Trans., SPWLA Eighth Annual Logging Symposium, (1967). Neutron values for Schlumberger "GNT" (Class A).
- D. T. W. Ehring, L. A. Lusk, J. M. Grubb, R. B. Johnson, M. R. DeVries, W. H. Fertl, "Formation Evaluation Concepts for Geothermal Resources," Trans., SPWLA 19th Annual Logging Symposium, (1978).
- E. Computed, based on tool calibration Z/A ratio of 0.5.
- F. J. Tittman and J. S. Wahl, "The Physical Foundations of Formation Density Logging (Gamma-Gamma)," Geophysics, Vol. XXX, No. 2, (April 1965).
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Media," Geophysics, Vol. XXI, No. 1, (January 1956).
Acoustical measurements made at 25°C and atmospheric
pressure.

- I. John I. Myung and Donald P. Helander, "Correlations
of Elastic Moduli Dynamically Measured by In-Situ
and Laboratory Techniques," SPWLA 13th Annual Logging
Symposium, (1972). Matrix values computed from
listed laboratory measurements and core analysis.
Laboratory transit time measurements made under
simulated overburden pressure.
- J. H. J. Ritch, "An Openhole Logging Evaluation in
Metamorphic Rocks," Trans., SPWLA 16th Annual Logging
Symposium, (1975). Log readings listed are the
average values from a range given in the reference.
Neutron values for Schlumberger "SNP" (Class C).
- K. Values from well logs:

Company - Reynolds Electric Company and Aerojet
Nuclear Company Well

Well - R. R. G. E. #2

Field - Raft River Geothermal

County - Cassia

State - Idaho

Neutron values from Schlumberger "CNL" (Class B) in
Limestone units converted from Sandstone log readings.
Matrix values computed from Schlumberger "MID"
charts, "Schlumberger Log Interpretation Charts,"
(1978).

- L. J. L. Dumanoir, Personal Communication, (1978). Neutron values for Schlumberger "SNP" and "CNL" (Classes C and b).
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- N. Orson L. Anderson and Robert C. Lieberman, "Sound Velocities in Rocks and Minerals," A VESIAC State-of-the-Art Report (1966). The average values listed are the arithmetic average of samples listed in the reference. Properties at STP.
- P. A. F. Woeber, Samuel Katx, and T. J. Ahrens, "Elasticity of Selected Rocks and Minerals," Geophysics, Vol. XXVIII, No. 4, (August 1963), p.658. Measurements made at STP without porosity correction.
- Q. Estimated, assuming nearly complete silification.
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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.
- T. Schlumberger Well Services, "Schlumberger Log Interpretation Volume I - Principles," (1972). Neutron

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- Y. W. H. Fertl, "Gamma Ray Spectral Data Assists in Complex Formation Evaluation," Dresser Atlas Division, Dresser Industries, Inc.
- Z. H. N. Edmundson and L. L. Raymer, "Radioactive Logging Parameters for Common Minerals," SPWLA Twentieth Annual Logging Symposium, paper no. 0, (June, 1979).

The "wet" and "dry" refer to the state before and after the sample is heated to 110°C and some water leaves the mineral. This may or may not be the same as true in-situ conditions but should indicate the direct and relative magnitudes of change.

The total gamma ray response is the theoretical response considering potassium only. Uranium and

thorium are not considered due to the wide range of possible content. The API value listed is derived from the computed value given in the reference as atoms/g and converted by the empirical relationship (also in the reference) for the borehole conditions of 10 lb/gal mud, 8-in. diameter hole and a 3-5/8 in. scintillation NaI detector type tool.

Neutron values for Schlumberger "SNP" (Class C).

AA. Same as reference Z. Neutron values for Schlumberger "CNL" (Class B).

AB. Gene Simmons and Amos Nur, "Granites: Relationship of Properties in-situ to Laboratory Measurements," Science, Vol. 162, p.789 (November 15, 1968).

Sigma values vary with pressure from 0 to 1000 bars.

AC Computed by author.

AD. C. Clavier, A. Heim and C. Scala, "Effect of Pyrite on Resistivity and Other Logging Measurements," SPWLA Seventeenth Annual Logging Symposium, paper no. HH, (June, 1976).

5. REFINEMENT of EXISTING INTERPRETATION TECHNIQUES and DEVELOPMENT of NEW ONES

5.c. FRACTURE DETECTION AND DEFINITION

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

With the many log-analysis techniques available, the most difficult problem is determining which method to use. Local experience is the best guide in this situation. The evaluation of exploratory wells will be more difficult, particularly if the data are limited.

The definition of a fracture system involves the location of the fractures (the subsurface 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, and the azimuth). It is also important to know if the fracture is open or plugged with solids such as precipitates from geothermal water, swelling clay, etc. The first indication of fractures in a well as it is being drilled may be a sudden increase in the rate of drilling. Also, if drilling mud is used, it is likely that fracture zones

will cause significant lost fluid circulation problems. Thus, the drilling record can sometimes be used to identify the location of existing fracture systems in a well. Similarly the drill-cuttings 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.

The techniques of interpreting well logs for detecting fractures vary a great deal. One method may involve only the inspection or interpretation of a single specialized well log. Other methods may require the comparison of two or more logs, with or without additional processing of the recorded values. The following sections discuss the logs or interpretation techniques currently used for the location of fractures.

Hole Geometry (Caliper Logs)

The caliper log measures borehole size with depth. Frequently, the rock chips away around fractures and causes the caliper to read greater than bit size. Since fractures normally are at an angle to the borehole, the hole enlargement may not be symmetrical. In these cases, a caliper with four or more arms delineates the borehole more accurately than the two or three arm calipers run with standard logging tools. Multiarm calipers may even allow the estimation of the dip of the fracture. The

acoustic caliper of Keys (1979) can provide borehole diameter measurements along four oriented axes with more resolution than devices with large mechanical arms.

When the borehole intersects vertical fractures, the hole may wash out in an out-of-round or elliptical shape with the largest axis paralleling the fracture plane. Figure 5.c.1 is a FIL log showing this characteristic as recorded with a four arm caliper. (FIL, Fracture Identification Log, is a Mark of Schlumberger.) Figure 5.c.2 is another example of an FIL log showing extreme rugosity in a fractured interval.

When a four arm caliper has not been run, comparison between other types of calipers may show out-of-roundness. For example, pad type devices, such as density or sidewall neutron tools, require heavy pressure to be applied to their source-detector pads to maintain contact with the borehole wall. This pressure is usually provided by a single back-up arm which, due to the large amount of pressure applied, follows the widest axis of a non-circular hole, thereby giving the largest borehole diameter measurement possible. Three-arm calipers run with sonic devices indicate an average diameter since the arms are normally linked together and do not have independent operation. In zones where the hole has washed out unevenly, the three-arm caliper will show a smaller diameter than the single-arm caliper, which reads maximum hole diameter.

Temperature

Temperature logs can indicate fractures by anomalies 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 would be expected from the general temperature gradient in the well. 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.

Acoustic

Several logs used for locating fractures are based on the detection of acoustical waves transmitted through the formation. Some commercially available logs are Micro-Seismogram (Welex), Variable Density Log (Schlumberger), Signature (Dresser Atlas), 3-Dimensional Velocity Log (Birdwell), and others. These logs display a full acoustic wave train in some fashion. Open fractures attenuate both compressive and shear waves, resulting in anomalous features on the logs. Time differences between signals arriving at the receiver, due to the nonsymmetrical arrangement of fractures, result in out-of-phase arrivals which further reduce the signal amplitude and distort the patterns.

The amplitude of the compressive or shear wave arrivals may also be recorded. The amplitude of sonic waves, both shear and compressional, may be reduced by reduced by a factor of as much as 10 or 20. The compressional wave has been generally found to be attenuated more by vertical and high angle fractures, while the shear wave appears to be more sensitive to horizontal and low angle fractures (Morris and others, 1964). Figure 5.c.3 is an example of a Welex Micro-seismogram and amplitude log over a section of the Niobrara shale in Colorado. The waveform shows attenuation and the amplitude curve indicates a reduction

over three intervals. Photographs of impression packers run in the lowest interval verify the existence of numerous open, near-vertical fractures. Production from the indicated intervals totaled 25.4 m^3 (160 bbls) of oil per day.

Not all fractured intervals will be readily identifiable from acoustic type logs. The following parameters, as described by Beck and others (1977), can affect the patterns and complicate the interpretation:

- Tool Centralization,
- Receiver/Transmitter Spacing,
- Hole Size,
- Lithology Changes, Shale Beds, etc.,
- Borehole Rugosity,
- Fracture and Bedding-Plane Orientation,
- Presence of Vuggy or Crystalline Porosity.

Porosity Comparison

It is commonly accepted that the sonic log responds primarily to intergranular porosity and does not measure porosity in fractures. The density and neutron logs respond to total porosity regardless of pore geometry. In a fractured zone, the porosity as derived from the sonic log would therefore be less than that derived from the density and/or neutron. This difference in porosity would be an indication of fractures.

This comparison technique only works when the formation is of a single, known lithology for which accurate matrix parameters are available for computing porosity. In mixed lithologies, computation of any porosity is

complicated and serious errors may be introduced. Also, if the formation is extremely heterogeneous, pad-type tools such as the density or some neutron tools, which measure the formation on one side of the borehole only, may give readings which are not representative of the formation and will, therefore, cause additional error in the porosity evaluation.

There is evidence that fracturing may sometimes cause sonic-derived porosity to be greater than expected rather than too low as discussed above. Cannon (1979) describes an empirical approach to evaluating the fractured Monterey shale in California by noting that production is best in intervals which exhibit a longer travel time than expected, when compared to the processed density and neutron logs.

Borehole Televiewer

This device uses an acoustical signal to create a "picture" of the surface of a borehole. Having orientation sensors, it is possible to determine the direction or orientation of features displayed by the "picture" in addition to location, width, and shape. 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. Working for the United States Geological Survey, Keys (1978 and 1979), has developed a borehole televiewer tool that can perform in 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 Hot Dry Rock Program of LASL, Raft River Geothermal Field in Idaho, the Roosevelt Hot Springs Field in Utah, etc.

Figure 5.c.4 is a reproduction of a borehole televiewer log taken in a well at Roosevelt Hot Springs, Utah and shows the intersection of a nearly vertical and another fairly steep fracture. Relatively tight, non-producing fractures are shown at the bottom of this interval.

Due to the frequent occurrence of lost mud circulation while drilling fractured reservoirs, many geothermal wells are drilled with water. This sharply reduces the cost of drilling mud and creates a more ideal condition for running borehole televiewer logs since a low-solids content in the borehole fluid produces better pictures. On the other hand, plain water as a drilling mud usually results in boreholes with larger and more frequent washouts which are detrimental to the critical centralization required for the borehole televiewer. The use of regular drilling muds can mask fractures and prevent their detection if mudcake builds up on the borehole surface. It should also be noted that the drilling process itself can break off chips of formation near the fracture, resulting in a wider aperture than exists in the formation.

When conditions are suitable, the borehole televiewer is the most definitive and direct method for locating and evaluating fractured formations.

Spontaneous Potential (SP)

In most formations which have the physical properties necessary for the existence of fractures, the SP is usually a wandering, featureless curve of little use. However, in these massive tight formations, fractures may cause a streaming potential to occur, resulting in deflections or anomalies in the recorded SP value. Such features

have been noted in the hot dry rock wells at LASL. However, the response cannot be related directly to the size or extent of the fracture system. A detailed description of the SP response in fractured intervals is discussed by Kintzinger and others (1977) in connection with experiments at the hot dry rocks program at Fenton Hill, New Mexico.

Resistivity Logs

The utility of resistivity logs in fracture detection is to confirm findings by other techniques. In massive, very low porosity formations, the resistivity is nearly infinite. The occurrence of a fracture, if filled with a conductive fluid, will cause a reduction in this very high resistivity.

Fracture detection is sometimes possible by a comparison of the readings of different types and spacings of measuring devices. A deep investigation induction tool will not be greatly influenced by the existence of a fracture. On the other hand, a shallow-reading resistivity device can be greatly influenced by a conductive fracture. This occurs because the heterogeneous characteristic of the fractures distorts the geometrical pattern or focusing of current flow and reduces the resistivity measurement. These anomalies can be noted only if a trend or relationship between the two devices has been established in non-fractured intervals. Caution must be observed in using this technique because other factors, such as shale or moved hydrocarbons, can produce similar responses. Figure 5.c.5 is an example of a Schlumberger Dual Induction-Laterolog 8 which is indicating fractures. Note the reduction of the Laterolog 8 reading at the depth indicated by the arrow.

Another possible approach to determining the presence of fractures from electrical logs is to plot on a log/log scale the formation resistivity versus the porosity of the formation. The slope of the line passing through the data is the cementation factor m in the relationship $R_o/R_w = a/\phi^m$ (Pickett, 1966). A formation with only intergranular porosity will have a cementation factor of approximately 2. The cementation factor for a fractured interval will be much lower, around a value of 1. Thus the slope determined from this plot could be utilized as a fracture indicator. As mentioned previously in the discussion of porosity comparison techniques, a computed porosity value may be in error when using pad type devices in fractured zones.

Compensated Density Log

Dual detector pad-type density logs were developed to provide a more reliable bulk density reading by correcting for the effects of mud cake and minor hole rugosity. The short spaced detector, having a very shallow depth of investigation, is greatly influenced by these factors and uses this characteristic in the compensation system. If the tool is positioned in front of a fracture when the borehole is smooth or in gauge, the short-spaced detector is more influenced by the fluid in the fracture than is the long spaced detector. The response is the same as if mudcake or hole rugosity were encountered. The resulting density correction value will be greater than expected for the existing conditions. Figure 5.c.6 is an example of a Schlumber FDC log recorded in a fractured interval. Note the large correction (cross-hatched) even though the caliper indicates a smooth borehole.

The following should be considered when inspecting a correction curve for indications of fractures:

- Mudcake will give a similar response to that given by a fracture.
- The borehole must be smooth. This may not be apparent on the caliper curve. Logs have been noted to have very large corrections while the caliper indicated a smooth borehole. On repeat runs over the same interval, the tool rotated to a different position and indicated no correction while the caliper showed a deep narrow washout. This can occur when the formations are not homogeneous.
- Being a pad type device, the density tool measures the formation on one side of the borehole only. It is possible to have fractures at a particular depth, but not on the side of the hole where the tool is reading.

Multiaarm Microresistivity Logs

The use of tools designed for determining formation dip have been used very successfully for locating fractures. Beck and others (1977), Brown (1979), Denoo (1978) and Schafer (1979) wrote papers describing the technique and all have examples from areas known to have fractured reservoirs. Beck and Schafer have related interpretation of these logs to oil production in localized areas.

The interpretation of the dipmeter log for fractures is quite different than the interpretation for determining formation dip information. In fact, presentations and scaling sensitivities of the log are usually quite different when the device is being used for fracture detection.

Normally, when running the dipmeter log, measurements are made by micro-resistivity devices which are designed to be very sensitive to resistivity changes. In normal dipmeter use, this allows correlation of the curves as they respond to bedding planes which cross the borehole. With these correlations and other orientation measurements, the magnitude of dip and direction can be determined. The sensitivities of the curves are adjusted to give the best overall recordings of low and high resistivity contrasts.

When logging in a potentially fractured reservoir, the sensitivities of the curves are set such that very little character is seen in the dense, low porosity, non-fractured zones. Reductions in resistivity readings often occur when a fracture is encountered. The micro-resistivity curves respond as described in the previous discussion on using resistivity logs for fracture detection. Shale stringers, thin permeable laminations, or fractures filled with conductive fluid which bisect the borehole at a low angle, will look nearly the same on the log. However, the likelihood of encountering low-angle fractures which have not been healed or filled, or which would contribute to fluid production, is small. The dipmeter device, as applied to fracture detection, works best in the delineation of vertical or very high angle fractures. The geometry of such fractures crossing the borehole can take one of many forms. Take, for example, a vertical fracture with a north-south orientation, and a four arm device with pad No. 1 pointed north. The fracture will be detected by pads No. 1 and No. 3, while pads No. 2 and No. 4 show no response. Other fracture geometries may not be detected, or may show up on only one pad. Brown (1979) presents several such possibilities. The orientation (azimuth) of the fracture can be estimated from the

knowledge of which pads are affected and by applying the orientation data run at the same time. The dip of the fracture is not estimated. Figures 5.c.1 and 5.c.2 are examples of the application of a dipmeter tool to fracture detection. These figures demonstrate two of the different types of presentations commonly used.

KUT Logs (Potassium, Uranium, Thorium)

West and Laughlin (1976) related increases in uranium content with fractures in the GT-2 hot dry rocks well at Fenton Hill, New Mexico. The fractures contain moderate concentrations of uranium that were precipitated from moving waters. An illustration of a Dresser Atlas Spectralog with this high uranium characteristic is shown in Fig. 5.c.7.

Rock Strength

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

The State of the Art of Fracture Detection

As discussed within this section, there are many log interpretation techniques for detecting fractures. This is probably because no one system seems to work in all places or under all conditions. Since fractures are critical to many geothermal systems, the effort to develop more reliable techniques is essential.

It should be noted that for most of the fracture-detection techniques listed, three different interpretations can result and have been observed.

- Fractures are indicated, and do exist,
- Fractures are indicated, but do not exist,
- Fractures are not indicated, but do exist.

Since these are possible variations in interpretation, experience and knowledge of the formation under evaluation is extremely valuable. The exploratory well must be evaluated by all available techniques in order to locate fractures.

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

- Resistivity,
- Hole washout,
- Excess density correction when hole is in gauge,
- Comparison of sonic porosity with porosity from neutron and density,
- 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 variable FRAC, the greater the likelihood for the existence of fractures. An analog playback of this variable is shown in Fig. 4.9.

(from Beck and others, 1977)

Fig. 5.c.1. Example FIL.

(from Beck and others, 1977)

Fig. 5.c.2. Example FIL.

MICROSEISMOGRAM
200 1200 **AMPLITUDE** **IMPRESSION PACKERS**

(from Walker and Kessler)

Fig. 5.c.3. Micro-Seismogram and impression packers.

Fig. 5.c.4. Borehole televiewer, Roosevelt Hot Springs.

Fig. 5.c.5. DIL with fracture indication.

Fig. 5.c.6. FDC with fracture indication.

SPECTRALOG SHOWING URANIUM IN BASEMENT FRACTURES

Fig. 5.c.7. Spectralog showing uranium in fractures.

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5. REFINEMENT of EXISTING INTERPRETATION TECHNIQUES and DEVELOPMENT of NEW ONES

5.d. TRANSIENT TEMPERATURE ANALYSIS

One of the most important goals of drilling a geothermal well is to find out the reservoir temperature. Unfortunately, the reservoir rock around the well bore gets cooled during the process of drilling, due to circulation of drilling mud, which is usually cooler than the formation being drilled. After circulation ceases, it may take anywhere from hours to months for the well to heat up to the true formation temperature, depending on the formation characteristics and the circulation time. Because of the high cost of drilling rig time, it is not possible to wait days or even very many hours to reach the true or equilibrium formation temperature in the well. Yet it is important to be able to estimate the equilibrium temperature while the rig is still on location so that important drilling and completion decisions can be made. This is particularly important for exploratory wells.

Many attempts have been made by drilling engineers and log analysts to obtain estimates of the equilibrium formation temperature from temperature logs run shortly after drilling or even from the maximum recorded temperature data from various logging runs in the same well. The aim of this section of the project is to review the possibility of estimating true formation temperature from transient temperature data taken during drilling or

logging operations or anytime before the true formation temperature has been reached in the well.

Literature Survey

As we have mentioned already, the temperature recorded during logging operations of a new well frequently is lower than the true static temperature. Schoepel and Gilarranz (1966) reported that early investigators "discouraged the use of bottom hole temperatures obtained when logging, under the assumption that the temperature would not be correct because the mud and formation were not in thermal equilibrium." They did conclude that the temperature buildup increases exponentially after circulation ceases and is dependent upon circulation time, hole size, initial temperature difference, and the specific heat of the drilling mud. They also concluded, since multiple and repeat logging runs are common, that maximum logged temperature measurement in deep hydrocarbon wells can be expected to be within 5% of the formation temperature because of the time required to remove the pipe and log the well a number of times. However, for geothermal wells, the maximum recorded temperature from the last log will not necessarily be within 5% of the initial temperature. The reason is that the temperature difference between the circulating mud and formation are usually much greater in geothermal wells than they are in oil and gas wells.

Edwardson and others (1962) numerically solved the equation that describes the temperature buildup at the well bore and at various distances away from the well bore for a dimensionless time parameter, $Kt_k/C_p r^2 = 0.4t_k$. *

* Nomenclature at end of section.

Fig. 5.d.1. Theoretical Horner temperature buildup.

This number is based on an "average" of the thermal properties of limestone, sandstone, and shale hydrocarbon systems and a wellbore diameter equal to 20 cm (7.875 inches). Figure 5.d.1 presents a family of dimensionless Horner temperature type curves. Plotted on the logarithmic scale is the ratio of the sum of circulating time and shut in time to that of shut in time. The dimensionless temperature is plotted on the linear scale. The numerator of the dimensionless temperature term is the difference between the initial temperature (T_i) and the well bore temperature (T_{ws}) evaluated at any shut-in time, Δt . The denominator is the difference between T_i and the temperature of the mud (T_m) when circulation ceased. Dowdle and Cobb (1975) reported that the "dimensionless temperature may be thought of as a constant multiplied by a real well bore temperature drop." In order to apply Fig. 5.d.1, the thermal properties of the reservoir must be known as well as the mud circulating time and the temperature for a particular depth of interest.

To simplify the complex problem, Edwardson and others (1962) assumed that the difference between the static formation temperature and the mud temperature remained constant during the circulation period. This is not strictly true since the mud which rises in the annulus becomes hotter as the well is drilled deeper. The change in mud temperature at any depth will be of the order of 1°F to 2°F per 100 feet drilled. However, Edwardson and others (1962) considered this change slow enough to allow them to take the mud temperature as being constant. This is not a good assumption for most geothermal wells.

The problem of temperature distribution in circulating mud columns has been investigated by Keller and others

(1974) as well as in other studies. The circulating model varies a little from one author to another. Each method requires a good knowledge of the geothermal gradient, which is not always available, especially in exploratory drilling. These methods solve for the temperature distribution in the annulus after the total depth of the well has been reached and only circulation is taking place. Thus, these methods cannot be used to find the mud circulating temperature that could be used with the dimensionless Horner-type temperature curves of Edwardson and others (1962) to determine the initial reservoir temperature.

Several investigators, for example, Timko and Fertl (1972) have suggested that the temperatures recorded during successive logging runs can be used to estimate static formation temperature. They recommended use of a Horner-type temperature buildup plot, with a time function similar to the conventional pressure method, for estimating static formation temperature. This type of analysis is based on the assumption that an average or constant heat flow from the formation occurs during circulation. Each of the investigators demonstrated the apparent applicability of the technique with an example.

Dowdle and Cobb (1975) investigated one of the papers referred to in the above paragraph (Timko and Fertl, 1972) and were "unable to find any theoretical justification for an analysis of this type." They showed that unlike the "diffusivity" equation used in describing pressure behavior, the inner boundary condition was not constant because the well bore temperature gradient was changing during circulation. Dowdle and Cobb (1975) pointed out that the nonlinearity of these Horner-type

temperature buildup curves was also due to the changing inner boundary condition. They did conclude that the method proposed by Timko and Fertl (1972) was reliable if both the well bore gradient changed very slowly and the mud circulation time was short.

Theory

The temperature distribution around the well bore is defined by the following partial differential equation:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} = \frac{C_p \rho}{K} \frac{\partial T}{\partial t} \quad (5.d..1)$$

This is known as the diffusivity equation in radial coordinates. Implicit in the use of this equation in this section are the following assumptions, some of which were used by Edwardson and others (1962) in their work:

- Cylindrical symmetry exists, with the well bore as the axis.
- Heat flow is due to conduction only.
- Thermal properties of the formation do not vary with time.
- The formation can be treated as though it is radially infinite and homogeneous with regard to heat flow.
- There is no vertical heat flow in the formation.
- The presence of a mud cake is disregarded.
- The temperature at the formation face is instantaneously dropped to some value and is maintained at this value throughout circulation.
- After mud circulation ceases, the rate of radial heat flow at the wellbore is negligible.

A few words should be mentioned to justify the last two assumptions.

First, consider the assumption of a constant mud temperature, which is also taken to be equal to the temperature at the formation face during circulation. In a previous paragraph, the reasons for the assumption of constant mud temperature used by Edwardson and others (1962) during the drilling of oil and gas wells were discussed. Figure 4.35 in Section 4 of this report shows a typical temperature profile for a geothermal well characterized by a finite linear gradient in the conductive zone above the geothermal reservoir and an almost zero gradient due to convection within the reservoir. As the well is drilled deeper, the mud temperature will increase rapidly until the depth is reached at which the sharp break occurs in the geothermal gradient. The zone below the break point is the producing zone. The formation and hence, mud temperature in this zone, remains relatively constant as the depth of the well is increased. Therefore, the mud temperature will not increase as drilling proceeds.

Considering the last assumption about heat flow into the borehole after circulation stops, the volume of fluid in the well bore is extremely small compared with the volume of formation whose temperature has been affected by circulation. Hence, the conduction of heat into the well bore can be neglected. Free convection in the system is negligible. It is assumed that the running of logging tools repeatedly in and out of the hole has no effect on the temperature buildup.

To provide a general solution, we will define dimensionless variables as follows:

$$r_D = r/r_w \quad (5.d.2)$$

$$t_D = K \frac{t}{c_p \rho r_w^2} \quad (5.d.3)$$

$$T_D = \frac{T_i - T(r, t)}{T_i - T_{wf}} \quad (5.d.4)$$

$$q_D(t_D) = \frac{q(t)}{2\pi K h (T_i - T_{wf})} \quad (5.d.5)$$

Equation (5.d.1) now becomes:

$$\frac{\partial T_D}{\partial r_D^2} + \frac{1}{r_D} \frac{\partial T_D}{\partial r_D} = \frac{\partial T_D}{\partial r_D} \quad (5.d.6)$$

The conditions placed on Eq. (5.d.6) are as follows:

$$\text{Initial} \quad T_D(r_D, 0) = 0 \quad (5.d.7)$$

$$\text{Inner Boundary} \quad T_D(1, t_D) = 1 \quad (5.d.8)$$

$$\text{Outer Boundary} \quad \lim_{r_D \rightarrow \infty} T_D(r_D, t_D) = 0 \quad (5.d.9)$$

Equations (5.d.6) through (5.d.9) completely describe the problem of production of heat from the formation at a constant well bore temperature.

Ehlig-Economides (1979) solved the problem of pressure buildup for a well produced at constant pressure. This is the same problem as temperature buildup described in this report except that Ehlig-Economides' (1979) solution deals with pressure instead of temperature. The

Fig. 5.d.2. Dimensionless temperature buildup ($T_{pD}=1$).

Fig. 5.d.3. Dimensionless temperature buildup ($T_{pD=5}$).

Fig. 5.d.4. Dimensionless temperature buildup ($T_{pD}=10$).

Fig. 5.d.5. Dimensionless temperature buildup ($T_{pD}=20$).

Fig. 5.d.6. Dimensionless temperature buildup ($T_{pD}=50$).

Fig. 5.d.7. Dimensionless temperature buildup ($T_{pD}=100$).

general solution for temperature buildup is given by the following equation in dimensionless form (Ehlig-Economides, 1979):

$$\frac{T_i - T_{ws}}{T_i - T_{wf}} = 1 + \frac{t_{pD}}{t} + \int_{t_{pD}}^t q_D(\tau) P_{wD} (t_{pD} + t_D - \tau) d\tau . \quad (5.d.10)$$

A computer program was developed by Ehlig-Economides (1979) to integrate numerically Eq. (5.d.10). This program was modified slightly and was used to develop a family of dimensionless temperature buildup curves shown in Figs. 5.d.2 through 5.d.7. In these figures, the abscissa is the Horner dimensionless time given by $(t_p + t)/t$ and the ordinate is the dimensionless temperature during buildup given by:

$$T_{Dws} = \frac{2 \pi K h (T_i - T_{ws})}{\bar{q}} . \quad (5.d.11)$$

Each figure is for a specific dimensionless production time (t_{pD}) given by $K t_p / C_p \rho_r w^2$.

It can be seen from Fig. 5.d.1 that if a conventional Horner analysis is used with early shut-in data, the temperature extrapolated for a dimensionless Horner time equal to one will always yield values of static temperature lower than they actually are. Dowdle and Cobb (1975) were the first ones to point this out in the literature. By looking at Fig. 5.d.1 again, it can be seen that using data from very long shut-in times (compared to circulation time), the Horner technique will yield the proper static temperature. Long waits required to obtain these data are time consuming and expensive. Discussions

on why very long shut-in data will yield the initial temperature is presented later in this section.

It is widely believed that straight lines can be drawn through the data when using the conventional Horner technique. The data used in these plots are usually taken during a short period of shut-in time. With this kind of information, the problem has been approached in the following manner.

$$\text{First define: } T_{Dws} = \frac{2\pi Kh(T_i - T_{ws})}{\bar{q}}, \quad (5.d.12)$$

where T_{Dws} is a function of both dimensionless producing (in this case, producing and circulating are synonymous) time, t_{pD} , and dimensionless Horner time, $(t_p + t)/t$. For limited ranges of dimensionless Horner time, a T_{Dws} curve can be approximated as being a straight line on semilog coordinates (See Figs. 5.d.2 through 5.d.7). The equation of this line is

$$T_{Dws} = T_{Dws}^*(t_{pD}) + b(t_{pD}) \log \frac{t_p + \Delta t}{\Delta t}, \quad (5.d.13)$$

where $T_{Dws}^*(t_{pD})$ is the intercept and $b(t_{pD})$ is the slope of the line. Both T_{Dws}^* and b are functions of t_{pD} . We now define T_{Dws}^* as follows:

$$T_{Dws}^* = \frac{2\pi Kh(T_i - T_{ws}^*)}{\bar{q}}. \quad (5.d.14)$$

Now substituting Eqs. (5.d.13) and (5.d.14) into Eq. (5.d.12) and rearranging, we have:

$$T_{ws} = T_{ws}^* - \frac{\bar{q}}{2\pi Kh} b(t_{pD}) \log \frac{t_p + \Delta t}{\Delta t}. \quad (5.d.15)$$

Letting:

$$m = \frac{\bar{q}}{2 \pi K h} b(t_{pD}) , \quad (5.d.16)$$

Equation (5.d.15) becomes:

$$T_{ws} = T_{ws}^* - m \log \frac{t_p + \Delta t}{\Delta t} . \quad (5.d.17)$$

Thus, a linear trend should be seen on the Horner plot. A false initial temperature, T_{ws}^* , is obtained when the line on the Horner plot (i.e., a plot of T_{ws} against dimensionless Horner time) is drawn through the data and extrapolated to a $(t_p + \Delta t)/\Delta t = 1$. "m" is the slope of this line.

Returning to Eq. (5.d.14) and rearranging, we have:

$$T_i = T_{ws}^* + \frac{\bar{q}}{2 \pi K h} T_{Dws}^* . \quad (5.d.18)$$

Multiplying and dividing the last term on the right side of Eq. (5.d.18) we have:

$$T_i = T_{ws}^* + \frac{q}{2 \pi K h} b(t_{pD}) \frac{T_{Dws}^*}{b(t_{pD})} . \quad (5.d.19)$$

Letting:

$$T_{DB}(t_{pD}) = \frac{T_{Dws}^*}{b(t_{pD})} , \quad (5.d.20)$$

Equation (5.d.19) becomes:

$$T_i = T_{ws}^* + m T_{DB}(t_{pD}) . \quad (5.d.21)$$

$T_{DB}(t_{pD})$ can be thought of as being a correction factor which can be used to approximate T_i from the slope and intercept (for dimensionless Horner time of 1) of a conventional Horner plot.

$T_{DB}(t_{pD})$'s were determined by least-square fitting a large number of T_{Dws} curves such as in Figs. 5.d.2 through 5.d.7 in ranges of $(t_p + \Delta t)/\Delta t$ where it was felt that the curve could be approximated as a straight line. These ranges of $(t_p + \Delta t)/\Delta t$ were chosen to be 1.25 to 2, 2 to 5, and 5 to 10. The intercept, $T_{Dws}^*(t_{pD})$ was divided by the slope, $b(t_{pD})$, to give T_{DB} . This procedure was carried out for a number of t_{pD} 's. Then a smooth curve was fitted through the points. The result is a curve that describes T_{DB} as a function of both t_{pD} and a range of $(t_p + \Delta t)/\Delta t$.

Discussion of Results and Application

The curves in Figs. 5.d.2 through 5.d.7 were evaluated using an "average" flow rate, $\bar{q}$. Horner (1949) suggested that the last established flow rate, $q(t_p)$, and a corrected flow time, $t_p^* = Q(t_p)/q(t_p)$, should be used in the buildup analysis. Since both $Q(t_p)$ and $q(t_p)$ are very difficult, if not impossible, to determine, an average flow rate was used so that the true producing time, t_p , could be used in the analysis.

The use of the average flow rate prior to shut-in is justifiable if the variation in q_D is small for $0 < t_D < t_{pD}$. Ehlig-Economides (1979) confirmed that this method was correct. The buildup equation in terms of the parallel problem of pressure buildup is

$$\frac{2 \pi K h (P_i - P_{ws})}{\bar{q}} = 1.1513 \log \frac{t_p + \Delta t}{\Delta t}, \quad (5.d.22)$$

where the constant, 1.1513, is the slope of the semilog straight line.

The nonlinearity of the curves in Figs. 5.d.2 through 5.d.7 is due to two reasons. First, large changes in $\bar{q}$ occur during circulation. Second, circulating time is usually too short. Nonlinearity also occurs in buildup curves for a system produced at a constant rate when flow time is short (see Fig. 5.d.1).

However, the curves in Figs. 5.d.2 through 5.d.7 do fall on the "proper" semilog straight line for very late shut-in data. Thus, the conventional Horner technique will always yield the correct static temperature if very late shut-in data is used.

As shown before, the correction factor, T_{DB} , used to multiply the slope, m , is a function of t_{pD} . This parameter t_{pD} , is a function of the thermal conductivity, K , specific heat, C_p , and density, ρ , of the formation as well as the well bore radius and circulating time. K , C_p and ρ are not always known, especially in exploratory wells. These properties can be estimated by examining the drill cuttings and using the data from the literature. It is not critical to know exactly what these thermal properties are. For example, $\pm 50\%$ error in t_{pD} will create an error in the calculated initial temperature of about 5.5°C (10°F). Of course, as the accuracy of t_{pD} increases, so does the accuracy of the calculated static temperature. If a conventional Horner plot was used without correcting T_{ws}^* , the calculated final temperature could be as much as 16.7°C (30°F) too low.

The following procedures for recording pertinent data to be used in the analysis of temperature buildup have been recommended by Davis and Sanyal (1979) and are presented here with a few modifications:

- A reasonably accurate time versus depth record should be kept.
- Zones subject to multiple circulations must be identified so that they will not be used in the analysis. The method proposed in this report is only valid for one circulating period.
- Special note should be made as to the depth of occurrence of any special cooling or "icing down" of the mud system. "Icing down" is a practice used in some geothermal wells to enable certain well logs to be run. It consists of adding ice to the mud to cool it, thereby prolonging the time that a logging tool can operate before the heat adversely affects its measuring system. Regions above the depth where "icing down" occurred should not be used in determining static temperature.
- If lost circulation occurs, the zones should be identified. The conductive model described in this report will result in erroneous temperatures under such conditions.
- When the well is logged using a continuous temperature log, the time when the run began and ended should be recorded. This is necessary to determine shut-in times.
- If there are any interruptions in the logging job, careful recording of the times should be made.

Nomenclature

b	=	slope of dimensionless temperature buildup curves
C_p	=	specific heat capacity, calories/gm-°C (Btu/lb-°F)
h	=	height or thickness of unit, cm (ft)
k	=	permeability, darcies
K	=	thermal conductivity, calories/sec-cm-°C (Btu/hr-ft-°F)
m	=	slope of straight line on Horner plot, kg/cm ² /log cycle (psi/log cycle)
P_i	=	Initial reservoir pressure, kg/cm ² (psi)
P_{ws}	=	buildup pressure at buildup time Δt , kg/cm ² (psi)
$\bar{q}$	=	average heat flow rate over circulating (production) time, calories/sec (Btu/hr)
q_D	=	dimensionless heat flow rate defined by Eq. (5.5)
r	=	radial distance, cm (ft)
r_w	=	well bore radius, cm(ft)
r_D	=	r/r_w , dimensionless radius
t	=	time, sec (hr)
t_k, t_p	=	circulating (producing) time, sec(hr)
t_D	=	dimensionless time, defined by Eq. (5.3)
t_{pD}	=	$K t_p / C_p r_w^2$, dimensionless circulating (production) time
Δt	=	shut-in time, sec(hr)
T	=	temperature, °C(°F)
T_D	=	dimensionless temperature defined by Eq. (5.4)
T_{DB}	=	dimensionless correction factor defined by Eq. (5.20)

T_{Dws}	=	dimensionless temperature defined by Eq. (5.12)
T_{Dws}^*	=	intercept of dimensionless temperature build-up curve at $(t_p + \Delta t) / \Delta t = 1$
T_i	=	equilibrium formation temperature, °C (°F)
T_m, T_{wf}	=	mud temperature when circulation ceased, °C (°F)
T_{ws}	=	shut-in temperature at time t , °C (°F)
T_{ws}^*	=	intercept of straight line on conventional Horner plot, T_{ws} versus $(t_p + \Delta t) / \Delta t$, °C(°F)
μ	=	fluid viscosity, cp (cp)
ρ	=	formation density, g/cm ³ (lbs/ft ³)
τ	=	time, sec (hr)

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SUMMARY AND RECOMMENDATIONS

The discussions and examples covered in the previous sections are replete with details concerning the state of the art of Geothermal Well Log Interpretation. A great deal of information is currently being acquired from well logs and much more will be gained in the future as additional data and experience are amassed. To enhance the techniques of interpretation, efforts in three primary areas are needed, two of which deal with the acquisition of more and better information.

- Indirect Techniques - The advance planning of the drilling techniques and data gathering efforts can create the environment for recording better quality logs and for getting the background information that is useful in interpreting logs.
- Logging Tools - Commercial tools available today are performing quite well under a wide range of conditions; however, new tools and tools with higher temperature ratings are also needed to adequately cover the remaining situations.
- Interpretation Techniques - There is a need to develop interpretation models and relationships for more routine processing and consistent results.

Each of these three areas have: (1) a certain state of the art being applied today; (2) methods which can be improved without requiring new technical developments; and (3) technical problems which need further research

and development. Of course, the cost/benefit ratio must be favorable for the application of existing techniques or the development of new ones.

Indirect Techniques

The majority of wells drilled in the geothermal or the oil and gas industry are of two types: exploration wells and development wells. In particular, the exploration well is drilled for the purpose of proving a geological concept and of evaluating in detail the formation characteristics. Depending on the operators knowledge and the geological complexity, development wells can be routine or almost as unpredictable as an exploration well.

Gathering information can begin as soon as the drilling process starts. Mud logging units may have the capability of measuring and recording a wealth of information throughout the entire drilling of a well. Information about the cuttings, drilling parameters, mud characteristics, drill bits, problems encountered, and other information are recorded on a log related to depth, with time notations. This type of information can be valuable to the log analyst when judging the environment under which the logs were run. Such services may not always be economically feasible on all wells drilled, but even a well documented diary of events and associated times can help to explain some logs responses and is a technique which does not require technical development. Of particular importance are mud characteristics, circulation times, temperatures, sample descriptions, and any unusual problems encountered while drilling.

The type of drilling fluid used can be a great influence in determining the type of logging tools which can be run, the tool response, and the borehole condition. A serious problem in drilling many geothermal wells is lost circulation of drilling fluids, particularly when fractures are encountered. In some areas, the loss may be so voluminous that water is the only economical drilling fluid possible. This situation usually creates poor borehole conditions for examining returns even if circulation is regained. Continuous caving and sloughing of the borehole walls makes the poorest conditions possible for well logging, and, in general, makes almost any type of evaluation and completion more difficult. The development of drilling techniques and more economical drilling muds for these conditions would greatly enhance the understanding and advancement of geothermal well log interpretation.

Designing the proper logging program and assuring that sufficient quality data is gathered is absolutely necessary if reliable interpretations are to be made. For example, the preferred type of resistivity log is a function of porosity and of the relationship between the resistivities of the mud filtrate and formation water (assuming electrically conductive drilling fluids). Some conditions may require both induction and laterolog type resistivity logs to determine true formation resistivity. Many companies that require the best evaluation possible from logs have set up departments with three primary functions:

- Design logging programs necessary for the evaluation desired, utilizing the types of logs which work best for the drilling fluid and formation characteristics expected in a particular well.

- Observe the logging operation to assure quality logs are run and to document events and information which are valuable during later evaluations. Also, by being present during this phase of the operation, action can be taken immediately if questions or problems arise. Additional evaluation or gathering of data may be impossible or too costly, after the well is plugged or completed.
- Interpret the logs which were recorded.

All too often, the logging operation is looked upon as something that has to be done so the rig can move on. It is emphasized that one of the main reasons for drilling a well is to COLLECT DATA FOR EVALUATION, and the logging operation is one of the MOST IMPORTANT steps in this process. When a qualified log analyst or staff is not available within an organization, consultants or the service companies can provide valuable advice in planning an operation and in interpreting the logs after they are run.

Logging Tools

As discussed in the first section, many logging tools are being routinely run in geothermal wells because of their extended temperature capabilities and/or by using special borehole cooling techniques. However, even when these tools with high temperature ratings are run in wells with somewhat lower temperatures, the logging problems multiply quickly and a great deal of rig time can be consumed in the logging operations. The need for increasing the temperature rating for existing tools is almost too obvious to mention. Increasing the endurance

(time spent exposed to elevated temperatures) is also very important, particularly with production logging tools.

The wireline companies serving the petroleum industry have continuously upgraded the available tools over the years because the search for petroleum has continuously reached new depths and higher temperatures. These higher rated tools do not have the temperature ratings required for logging many geothermal reservoirs. To improve the state of the art in high temperature rated electronics, the DOE has sponsored research programs which have resulted in components and equipment capable of operating in extremely hostile conditions. These tools, however, have usually been specialized (e.g., pressure and temperature) and improvements have not been made directly on upgrading the routine logging tools which are the basis for most log interpretation models.

Interpretation Techniques

The advancement of Geothermal Well Log Interpretation can be approached from many directions. Improvements of individual log interpretation, and techniques using multiple log suites can be made. Some of the individual tool types which are currently in use are:

Density Logs

Compensated density logs have been in commercial use for some time and produce very reliable results. A smooth borehole is required for quality recordings. In rock other than quartz, limestone, or dolomite, the

apparent matrix value as "seen" by the density tool may be quite different from the specific gravity of the rock or mineral. Section 5.b of this report deals with establishing additional matrix response information. Schlumberger Well Services is field testing a new generation density tool which further interrogates the raw tool measurements and produces an additional curve which can be related to lithology. In the future, this type of measurement may be used as another input to models for the determination of complex lithology.

Acoustic Logs

The measurement of compressional transit time has been a common measurement for many years. Advancements in recording techniques are currently being made to allow digital processing of the entire signal. This should lead to more reliable values for amplitudes and shear wave transit time determinations. These data will improve the interpretation techniques for the evaluation of mechanical strength properties.

As pointed out in Section 4 (Raft River Wells), acoustic recordings can be questionable. Evaluation at the well site can point out such problems and in some cases, result in more information than originally anticipated.

Neutron Logs

Of the three primary "porosity" logs, the neutron tools are the most complex. The tool may be measuring thermal or epithermal events; may be a pad type tool; two detector compensated or single detector; may use one of

many detector types; or may utilize different source-detector spacings. Each of these design features may change the lithologic response.

Additional information is needed to establish the response of these neutron tools to rocks other than those normally encountered in most petroleum reservoirs. Advances in this area can be made by two directions of effort, with the best solution being a combination of both.

- 1) Utilize Raw Data - Most neutron tools incorporate some type of function former to convert count rates to porosity. The two detector, compensated tools compute porosity from the ratio of the near to far detector count rates. This is satisfactory for normal use, but may be a hindrance for rocks or minerals encountered in geothermal wells. The true response of the tool may be masked or distorted.
- 2) Additional Calibration - Test pits or standard test wells with known lithologies should be utilized to determine the response of the many neutron tools. LASL has made available such facilities in two test wells (East Mesa and Roosevelt Hot Springs) and plans are currently underway to establish additional test pits to compliment the existing USGS facilities in Denver, Colorado. These new test pits will advance the understanding of other log response in different lithologies and varying pore geometries (i.e., fractures with different orientations).

Resistivity Logs

Tools which can measure extremely high resistivity values with greater accuracy than those currently available, may be valuable in the interpretation of very tight formations encountered in many geothermal wells. Depending on the information available, these recordings may help in interpreting porosity or water quality.

Other Logs

The geothermal industry should make every effort to test and evaluate logs other than the "usual" type of borehole logs. Examples are: electromagnetic propagation, dielectric, magnetic susceptibility, spectral gamma ray, and gravity surveys. It is not possible to predict exactly how each of these measurements may be applied, but serendipity has been known to occur in log interpretation. Any one of these tools has the potential of solving some type of problem in geothermal log interpretation.

Geothermal Log Interpretation Models

Section 5.a discussed at length the establishment of interpretation models. With greater understanding of tool response to geothermal type rocks, these models will be more reliable. Since many of the sections of this report detailed the specific problems and parameters needed to advance geothermal well log interpretation, they will not be reiterated here. The solution to these problems can be advanced in the following programs.

Case History Studies

Many studies in the past have approached interpretation problems with various techniques. Several studies have made definite advancements or answered significant questions in the geothermal well log interpretation field. The effort now should be directed toward more specific answers which can be used in predicting well performance and field operation. This will require the comparison of well logs and interpretations to both individual well tests, production characteristics, and field results. To be economically useful, geothermal well log interpretation must come up with answers which directly answer the questions:

- Will this well produce?
- How much will be produced?
- How does the well compare to others in the area (both performance-wise and geologically)?

Data Gathering

A great deal of data on geothermal wells has been amassed in the last few years. However, gathering all the data on a particular area for use in a comprehensive study is extremely difficult. Bits and pieces of information will often not allow a logical approach or result in satisfactory solutions to the problems of geothermal well log interpretation.

If complete data were available in a few representative areas, significant contributions could be made to the state of the art of geothermal well log interpretation. These data should include:

- Data and interpretations of exploration techniques (seismic, electrical, etc.),
- Data and interpretations of geological and geochemical studies,
- Complete drilling records (dates, times, mud conditions, problems, samples, etc.),
- Core analysis for relating log response to formation characteristics,
- Complete logging suites,
- Results of individual well performance,
- Results of field performance.

Only with this type of effort, will geothermal well log interpretation become as routine as the evaluation of petroleum reservoirs today.

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 Fig. 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 Figs. 4.1 and 4.3. However, Plots A and B are extended to include the 100% water or fluid point. Porosity, then, is scaled between the matrix and fluid points from 0% to 100% porosity.

To compute M or N, any pair of points on a plot (the log readings) and the 100% fluid values are used in the equation. The results of calculating M and N are actually the slopes of that lithology line. (Mathematically, M and N are not the true slopes of the lines, as the equations are arranged and factored to give positive numbers with magnitudes in the same range.) For any given lithology, any set of points (representing any porosity value) will result in the same M or N value. For example, the M and N values computed using the log readings in 30% limestone will be the same as the M and N values computed using the log readings in zero percent limestone ($M=0.817$, $N=.585$). Computations using the log readings in sandstone of any porosity will also be the same, but will be different than those for limestone. M and N are therefore two values from three logs which are independent of porosity but change with lithology.

Figure 4.4 is an example of the M and N values computed from log readings on well GT #2. The M and N values for any

porosity of sandstone, limestone or dolomite are marked. Note that a range of N values for dolomite is shown due to the nonlinear response of the neutron (see Fig. 4.1). Only one value of M exists for dolomite because the density and sonic response to porosity is linear (see Fig. 4.3). The theoretical value of M and N for any type of rock can be computed if the matrix (0% porosity) values are known and the neutron response is linear.

Fig. A.1. Plot and equations for M and N.

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