BOREHOLE GEOPHYSICS IN GEOTHERMAL WELLS--PROBLEMS AND PROGRESS

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Surface geophysical techniques are readily adaptable to exploration for and evaluation of geothermal reservoirs because existing equipment and interpretive models can be used. In contrast, the application of borehole geophysics for these same purposes requires the development of equipment to operate dependably in the very hostile environment of some geothermal wells. After equipment has been developed and tested, its response must be calibrated with respect to required parameters such as lithology and porosity. This is difficult in geologic environments where there is practically no experience in well-log interpretation. The desired final products are reliable data to guide exploration for geothermal systems, and to aid in reservoir evaluation, modeling, and development, in the ways in which well logs are routinely used in the petroleum industry. Researchers in geothermal exploration are still some years from achieving the level of application already attained in petroleum exploration and development. This deficiency is receiving some attention from the U.S. Energy Research and Development Agency (ERDA) and the U.S. Geological Survey. The two agencies cosponsored a workshop on Geophysical Measurements in Geothermal Wells in September 1975 (Baker, Baker, and Hughen, 1975). Sandia Laboratories had previously summarized the state-of-the-art in a report on "Well-Logging Technology and Geothermal Applications" (Baker, Campbell, and Hughen, 1975). For several years the U.S. Geological Survey has had a research program to develop logging instrumentation and log-interpretation techniques for geothermal applications. This summary describes some of the results of that research effort.

Equipment Problems

The research project on borehole geophysics in the U.S. Geological Survey has several high-temperature logging systems under development and test. The following probes rated at 250°C and 10,000 PSI ($6.896 \times 10^7 N/m^2$) are being used for experimental geothermal well logging: temperature, fluid conductivity, caliper, natural gamma, spectral gamma, non-compensated gamma-gamma, non-compensated neutron, 16 inch and 64 inch normal resistivity, spontaneous potential, single-point resistance, and acoustic televiewer. Upgrading for high-temperature operation is planned for several other logging probes which now operate to approximately 150°C (Celsius); these include acoustic velocity, focused resistivity, induction, compensated gamma-gamma and flowmeter probes, and a water sampler. Many of these probes are of stainless steel; development of probes that are more resistant to long exposure to the highly corrosive fluids found in some geothermal wells has not yet been started.

The logging probes listed above are operated on two research trucks that utilize high-temperature (250°C) armored cable; 6,000 feet (ft) (1829 meters (m) of four-conductor and 16,000 ft (4877 m) of seven-conductor cable. Both trucks are capable of recording data from wells simultaneously in analog and digital forms. Digital data can be recorded on computer-compatible 7- or 9-track magnetic tape, or punched or printed on paper tape. Data are usually recorded at 0.5 ft (0.15 m) intervals, and output from as many as seven sensors can be recorded simultaneously along with depth information to the nearest 0.01 ft (0.003 m). We also have magnetic-tape systems for recording gamma spectra and the full acoustic wave form digitally. All these digital data are then entered without modification into the Survey's computer in Denver for quantitative analysis.

Two general approaches are used to develop geophysical logging probes capable of operating at high temperatures. The simplest method is to isolate all the electronic components and sensors from the borehole environment by means of a stainless steel dewar flask inside a high-pressure housing. Heat-sink material that changes state below the maximum operating temperature of the components is incorporated in the flask. These tools are usually designed for 10 hours of operation at 250°C. The major drawback to this approach, which we use for several high temperature probes, is the build-up of heat from power dissipation in the electronics. Internal heat, which cannot escape from the flask, may cause drift in output signal.

A second approach is to replace all electronics, mechanical components, and materials for operation at 250°C. For most logging probes this is not possible because many of the necessary high-temperature components and materials do not exist. The Energy Research and Development Agency is funding a number of development efforts in private industry to correct this deficiency. In the meantime development of a dependable high-temperature acoustic televiewer, so important to the geothermal industry, has been an expensive and time-consuming project. Our approach for the televiewer has been a combination of the two techniques described above. All electronics are installed in a dewar flask with heat sink-material and the motor-magnetometer-transducer section is designed for operation in high temperature fluids. The status and application of this one-of-a-kind probe will be described later.

Testing of probes developed for geothermal logging has also been a problem. Components and sections can be tested in laboratory ovens, but until recently there has been no high-temperature, high-pressure, wet chamber available for testing assembled probes. Even this kind of a test does not fully simulate logging environments. There is no substitute for actually logging a hot well. We are attempting to combine in-hole testing with development of calibration data and log-interpretation techniques for the probes listed above. Some of our high-temperature probes are dependable and stable and others are not, which is similar to the experience users have had with commercially available high-temperature logging services.

In-Hole Gamma Spectrometry

The natural gamma log provides no information on the relative concentrations of uranium, thorium, and potassium which contribute to the total gamma radiation emitted by all rocks. In-hole gamma spectrometry does provide data on the relative concentrations of these naturally occurring radioisotopes and has several potential applications to studies of geothermal reservoirs. This log provides more diagnostic information on lithology than can be obtained from the gross radiation recorded as a natural gamma log, and the concentrations of the radio-elements are related to sources of radiogenic heat in rocks.

Several geothermal investigators in Los Alamos report that the gamma spectral log is one of the most useful logs run in the crystalline basement rocks penetrated by their deep wells (West and Laughlin, 1976). The spectral logs provided unique data for the identification of such rock types as hornblende-biotite schists and leucocratic monzogranite, and for correlation between holes. The presence of high concentrations of radium-equivalent uranium in fracture zones is evidence of the mobility of uranium and aids in the location of fracture zones that formerly had a relatively high intrinsic permeability. The spectral log may therefore provide information related to the source of radon gas reported to be abundant in some geothermal waters and which might constitute an environmental problem in the development of geothermal energy.

Continuous spectral logs are available from one commercial service company and we developed and are now testing a high-temperature spectral logging probe. We have developed the capability of transmitting the spectral data through 16,000 ft (4877 m) of logging cable and of digitizing the spectra in the logging trucks. Project personnel also wrote computer programs for energy shifting and stripping of complex gamma spectra (Eggers, 1976). By means of these techniques, quantitative analyses for radioisotopes can be made with equipment that is properly calibrated for the borehole environment. Calibration is now done by utilizing laboratory analyses of core.

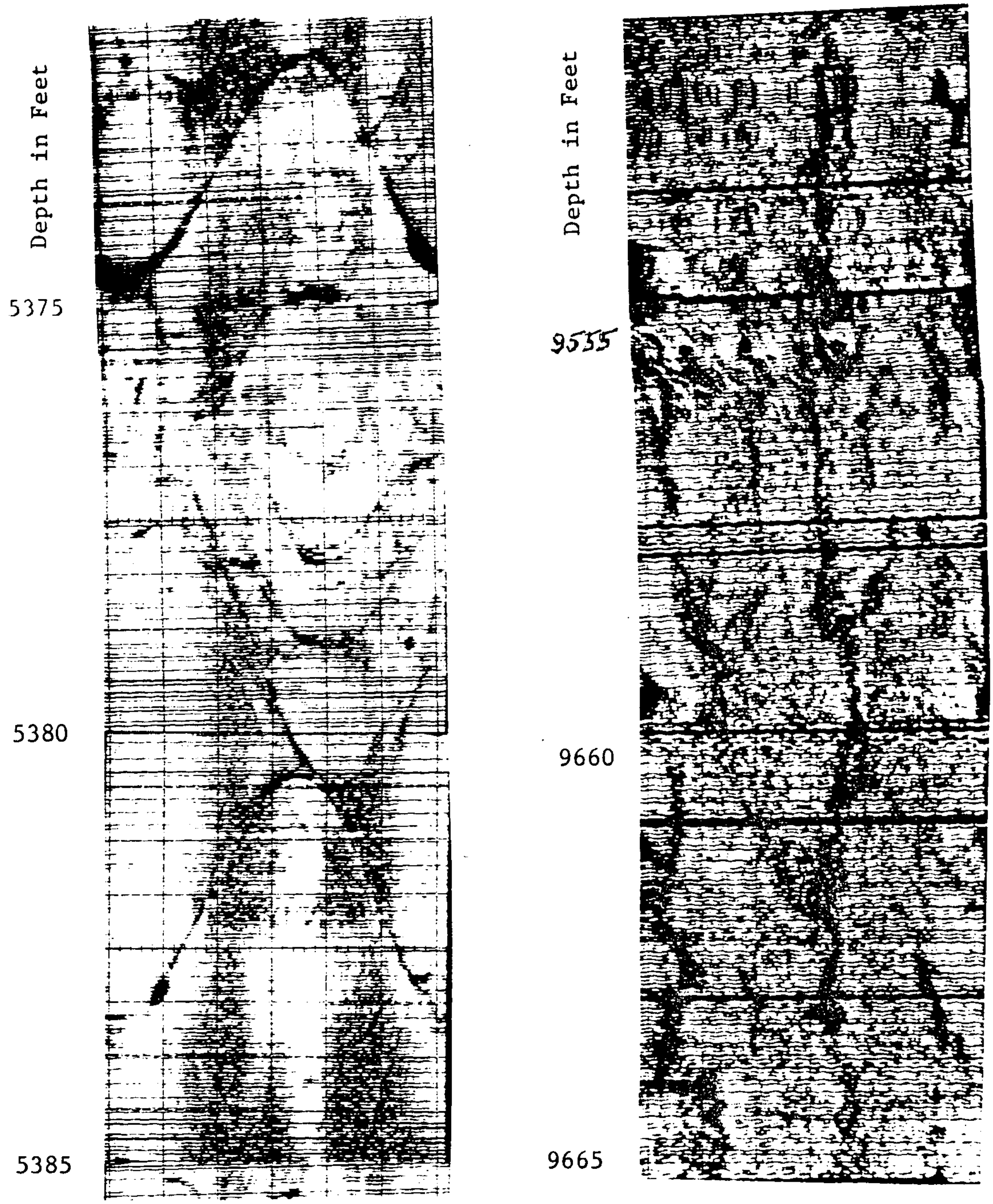
Acoustic Televiewer

The acoustic televiewer provides the most reliable and accurate data on the location and orientation of fractures and other types of secondary porosity. The probe employs an acoustic transducer which is rotated at three revolutions per second. Each rotation of the transducer is displayed as a sweep on an oscilloscope at the surface, and the sweeps are triggered on magnetic north by a magnetometer in the probe. The intensity of the scope trace is a function of the amplitude of the acoustic signal reflected from the wall of the borehole. A camera is used to record the successive sweeps, which are combined to produce a picture of the borehole wall as if it had been split along the north side and opened out into the plane of the picture. The strike and dip of fractures and other planar features can be calculated from the televiewer log and a caliper log (Zemanek, 1969). The acoustic televiewer log can resolve features as small as 1.5 mm, and it can be used in holes filled with drilling mud, water, or oil. Our televiewer systems also have available oriented acoustic caliper outputs that produce four very high resolution traces at North, East, South and West. These data, combined with the televiewer log, provide a three-dimensional model of fractures and other openings.

While televiewer probes were developed 8 years ago and have been used by several service companies, the only high-temperature televiewer probe built to date is being developed under contract for, and tested by, the U.S. Geological Survey. It has been used experimentally to log geothermal wells at Marysville, Mont.; Raft River, Idaho; Long Valley, Calif. and Los Alamos, New Mexico. Although it has operated at temperatures as high as 200°C for many hours it is still not dependable, and all component and material problems have not yet been solved. Despite these problems we are encouraged by progress to date and look for further improvement of the system.

The potential significance of a probe that reveals individual openings in the borehole wall is illustrated by a statement by geologists for a major company involved in the development of one important geothermal reservoir, that the orientation of fractures would be the most important data that could be obtained from geophysical logs. This statement is based on the hypothesis that fractures of one orientation are more likely to produce steam than those of another, and that information on the distribution and orientation of fractures as a function of depth would allow wells to be drilled directionally at the best angle to intersect the producing fractures.

Natural fractures are very abundant in most of the geothermal wells we have logged; some of these wells attain depths as great as 10,000 ft (3048 m). Fracture sets have been observed with favored orientations that may be consistent over several thousand feet of hole. Log A in Fig. 1 is a section of televiewer log made with the high temperature probe in a well in Long Valley, Calif. Several fracture sets with different orientations are clearly shown. Considerable difference in the character of fractures has been noted in such logs, and the data being collected will make possible a study of the relationship of water contribution to the orientation and character of the fractures. We have also used the televiewer to log a well before and after hydraulic fracturing as an essential part of state-of-stress studies in California and in Colorado. Fractures induced artificially as part of the Los Alamos Scientific Laboratory's hot-dry-rock program were observed during logging in a deep well in New Mexico. Log B in Fig. 1 was made in this well and shows a section of a hydraulically induced fracture system, which is apparently both vertical and branching. If hydraulic fracturing becomes an important procedure for the stimulation of geothermal wells the televiewer will be needed to provide information on the fractures produced. Study of subsidence caused by the withdrawal of geothermal fluids is another potential application of the televiewer; this may prove to be one of the best ways of estimating the amount of compaction in sediments penetrated by wells. It has high resolution and can therefore be used to measure the shortening of each length of casing caused by compaction. This can be done by locating very accurately collars, perforations, or other irregularities in casing.



Log A--Long Valley, California

Log B--Los Alamos, New Mexico

Figure 1.--Acoustic televiewer logs made in geothermal wells

Computer Interpretation of Logs

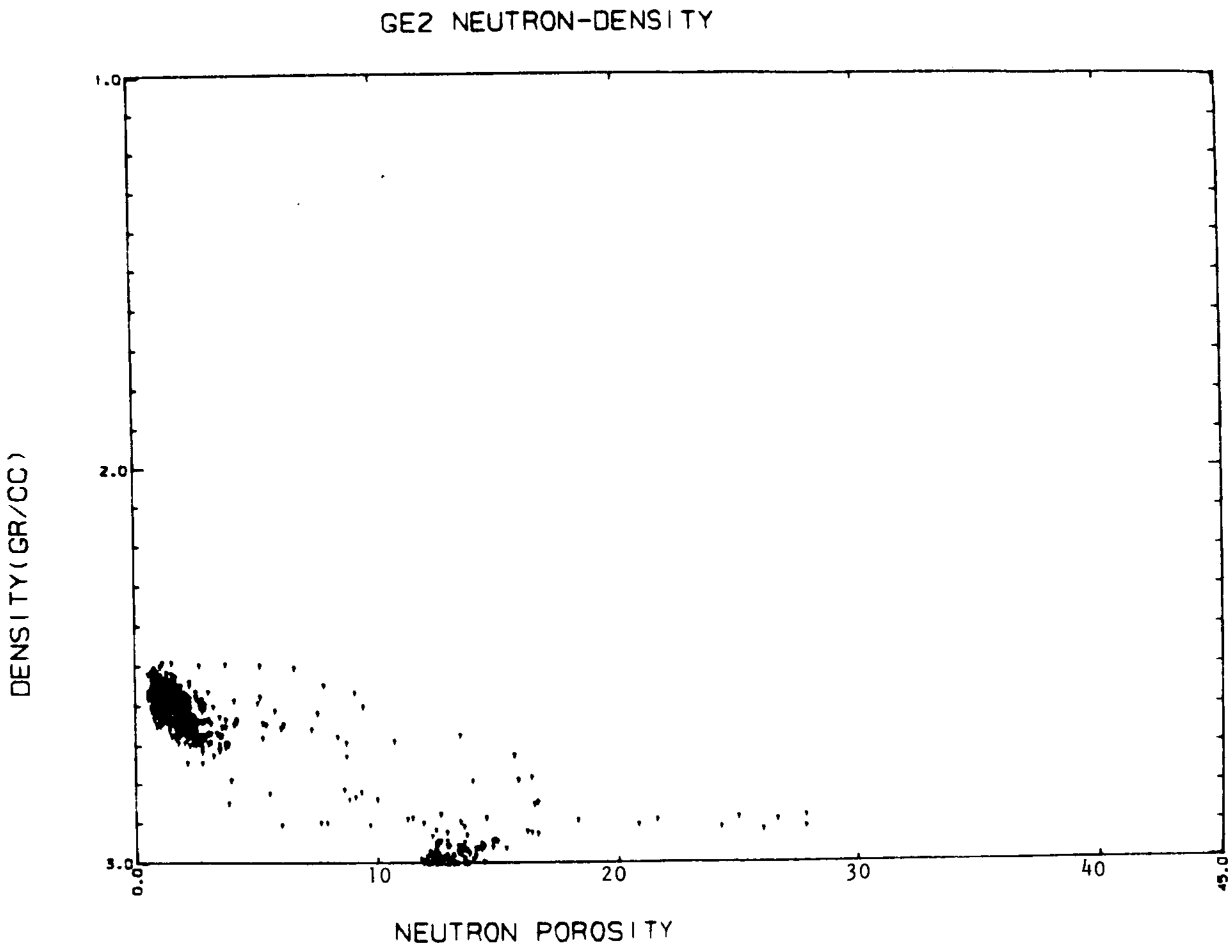
Four types of logs respond to changes in porosity in a lithology-dependent manner: the neutron, acoustic velocity, gamma-gamma, and resistivity logs. Resistivity logs, however, also depend on the conductivity of the interstitial fluid. A typical petroleum-oriented technique is to crossplot two of the three lithology-dependent porosity logs. If the rock type is limestone, sandstone or dolomite, or a mixture of any two of these, the cross-plots may indicate lithology and provide estimates of porosity values corrected for lithologic or matrix effects. We are attempting to use this technique to interpret geophysical logs of the wells in the Raft River Basin, Idaho.

Fig. 2 is a computer-generated plot of density from a commercial gamma-gamma log and of porosity from a commercial neutron log, assuming a sandstone matrix. The plot is for the depth interval 5400 to 5900 ft (1646 to 1798 m) in the Idaho National Engineering Laboratory's well RRGE-2. It is apparent from the plot that two distinct lithologies or porosities are present. Nearly all the points clustered around 13% apparent porosity and a bulk density of 3.0 g/cc correspond to the depth interval from 5690 to 5760 ft (1734 to 1756 m). The cut-off at 3.0 g/cc is due to setting of the scale for the gamma-gamma log at value suitable for a typical oil-field environment. A more effective scale would have accommodated the higher densities encountered in the igneous and metamorphic rocks. This demonstrates the importance of having a log analyst at the site who is familiar with the geothermal environment. Data from cuttings and core indicate that the interval from 5690 and 5760 ft (1734 to 1756 m) is biotite schist. Biotite has a bulk density of 2.8 to 3.4 g/cc.

The cluster of points at a bulk density of approximately 2.6 g/cc and an apparent porosity of 2 percent represents quartz monzonite, which is found above and below the biotite schist. If the sandstone, limestone, and dolomite lines were added to the plot in Fig. 2 the quartz monzonite would fall between 0 and 5 percent on the line representing sandstone porosity. This relationship is quite reasonable because the minerals in quartz monzonite have grain densities that average near 2.65 g/cc, a value commonly assumed for sandstone. The crossplot points for biotite schist do not fall near any of the lithologic types on available cross-plots. This illustrates the need for development of calibration data and interpretive techniques for the rock types found in geothermal areas but not found in petroleum-producing areas.

Project personnel have developed computer techniques to compute lithology-corrected porosity, matrix density, matrix velocity, acoustic porosity, secondary porosity, apparent water resistivity, mineralogy, thermal conductivity, and heat flow in a limestone-dolomite section in Texas (Merkel, MacCary and Chicko, 1976). Figure 3 shows some of these curves generated by the computer. Lithology was solved as a function of the three porosity logs (neutron, gamma-gamma, and acoustic velocity) by means of a linear programming algorithm.

Figure 2.--Computer-generated crossplot of neutron and gamma-gamma logs for Raft River well GE2, depth interval 5,400-5,900 feet (1646 to 1798 m)



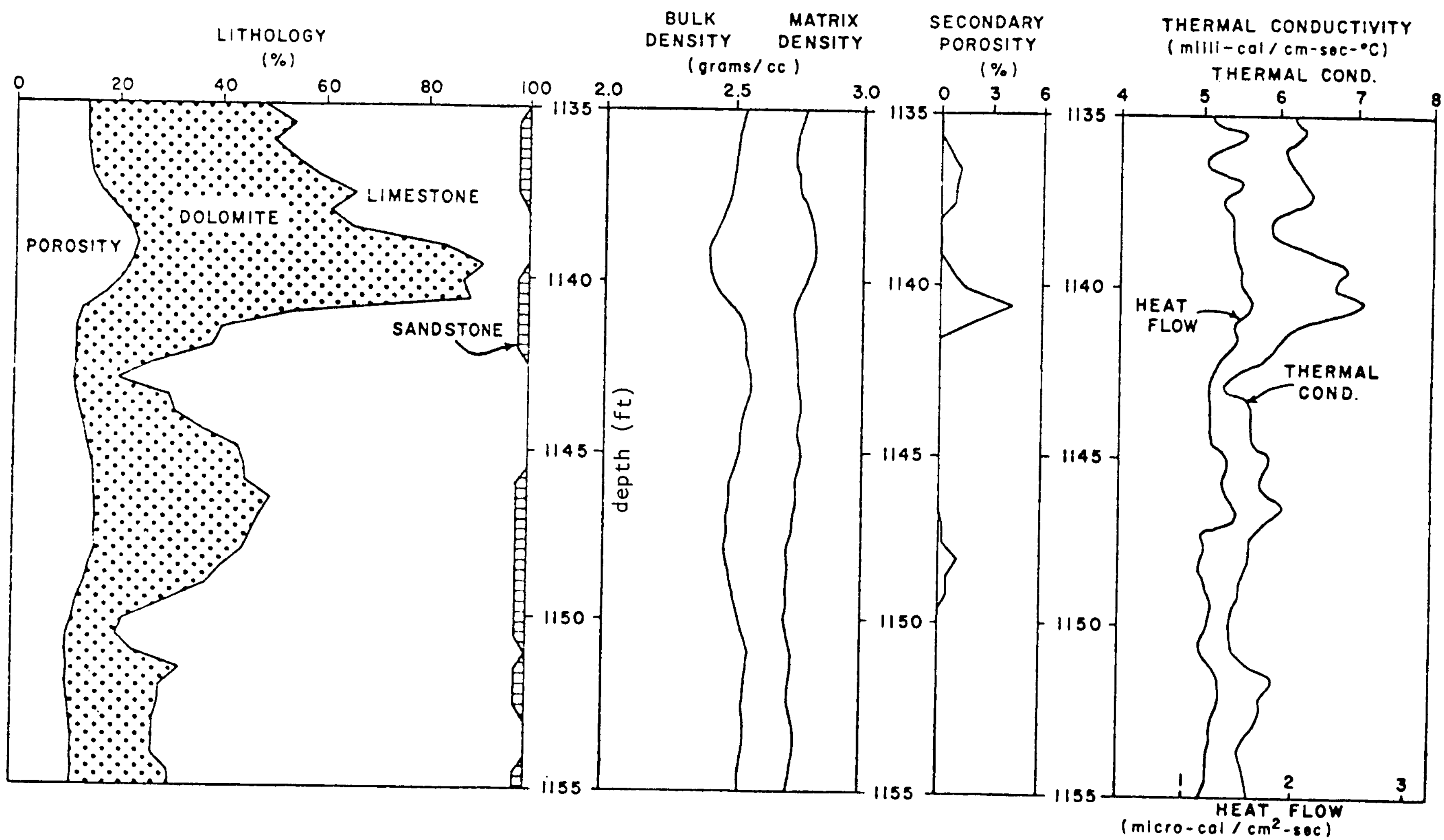


Figure 3.--Computer-generated curves for the Randolph number 1 test hole near San Antonio, Texas

A thermal conductivity log was generated in the computer using the results of the mineralogy program and a geometric mean equation that has been found to represent most effectively the relationships between mineralogy and thermal conductivity (Sass and others, 1971); Merkel, 1975). A temperature-gradient log was generated using the temperature log and a delta-Z of 10 ft. The product of thermal conductivity and thermal gradient produced a heat-flow log.

Conclusions

The application of borehole geophysics to the development of geothermal energy is still in its infancy but equipment problems are being solved and progress is being made toward quantitative interpretation of the logs in environments where previous experience does not exist. These efforts will be furthered by the availability of core, core analyses, and test information from various geothermal environments and by increasing time available for logging those wells where other data are available.

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