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LOCATION AND CHARACTER OF FRACTURES IN GEOTHERMAL WELLS

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ABSTRACT

Fractures are the major conduits for movement of hot water and steam in most geothermal reservoirs. It is important to understand these fractures in order to decrease costs and increase the effectiveness of geothermal exploration and development. Data on the location, orientation, apparent width, water movement, and relationship of fractures to lithology have been obtained from borehole geophysical logs of geothermal wells. Large open fractures produce anomalies on most kinds of logs, but the correct interpretation of these logs requires the synergistic analysis of all available data. Because log analysis is not well understood in the altered igneous and metamorphic rocks common in geothermal reservoirs, the interpretation of fractures in this matrix is even more difficult. Borehole-acoustic techniques with a wide frequency range are the most useful in providing umambiguous fracture information, but nuclear, electric, mechanical, and temperature logs also have added to our knowledge.

INTRODUCTION

Most hot water and steam produced from geothermal wells moves through fractures. In many reservoirs the penetrating of open fractures by a drill hole makes the difference between an economic well and a dry hole. Information on the depth and orientation of producing fractures enables new wells to be located and drilled directionally in order to increase the chance of intersecting permeable fracture zones. A number of borehole geophysical-logging techniques can provide fracture information, however, the hot environment in geothermal wells and the lack of knowledge about reservoir rocks makes the logs difficult to interpret. We have used borehole geophysics to study fractures in crystalline rocks, in order to assist in the development of geothermal energy and to evaluate sites for the disposal of radioactive waste. Considerable progress has been made in the development and modification of equipment to obtain fracture data at high temperatures. Furthermore, the analysis of logs in altered igneous and metamorphic rocks is much better understood than it was 5 years ago.

Natural fractures as used in this report include all megascopic breaks in rocks, due to natural causes, regardless of the presence or absence of displacement. Therefore, cracks, joints, and faults are included and they may be open, closed, or filled. Hydraulic fractures are those induced either intentionally or accidentally during or subsequent to the drilling of a well. The term microfracture here includes fractures only visible under a microscope. At the present time microfractures are undetectable in a well except as part of the overall porosity.

This paper summarizes the kinds of fracture information needed, the downhole method that might provide that information, and presents examples of fractures in wells in several different geothermal reservoirs. Finally some research techniques are discussed that may improve our understanding, and thus, our ability to predict water movement through fractures.

FRACTURE LOCATION AND ORIENTATION

Information on the depth at which fractures are intersected and their strike and dip is absolutely essential to an understanding of the geometry of a fracture system. Most kinds of geophysical logs will record an anomaly at a major open fracture, but few such anomalies can be interpreted with certainty. Many of these anomalies are due to the effect of local increases in well diameter on the response of the logging probe. A poorly cemented layer of shale or hydrothermally altered vocanic rock may cave and produce the same kind of log response as an open fracture. Thus, it is important to know as much as possible about the rocks penetrated by a well and the response they produce on geophysical logs. Significant movement of hot fluids along a fracture zone usually produces hydrothermal alteration that can be a guide to production zones.

Only magnetically oriented logging probes, like the acoustic televiewer and the dipmeter, can provide data on the strike and dip of fractures. Many deep geothermal wells are either accidentally or intentionally deviated from the vertical. An accurate record of the degree and direction of deviation is, therefore, essential if the true location and orientation of fractures in the well bore is needed. Furthermore, concentrations of magnetic minerals and extreme well deviation from the vertical may produce additional errors in the measurement of fracture orientation by techniques using the Earth's magnetic field.

Information on the location and strike and dip of fractures can be plotted as a function of their production if such information is available. In a single reservoir it is likely that fractures of one or several orientations are the most productive. Such information can be used to guide exploration and development. If enough fracture information is available, cross sections showing possible correlations between wells or even a three-dimensional model, would be useful to guide the location and deviation of wells.

FRACTURE CONTINUITY

The continuity of fractures and their connection with other fractures is important in determining their productivity. Fractures that appear on logs to be very open near the well may be shown by hydraulic tests to produce little flow because they lack continuity. Although many fractures may be logged in a geothermal well, most of the production usually is derived from a few major open fractures that are part of an interconnected fracture system. Furthermore, other fractures that appear to be open at the wall of the hole may be found to be nonproductive. No single-well geophysical logging techniques are presently available to investigate the continuity of fractures between wells. As described later in this paper, acoustic-logging techniques offer some promise for investigating fractures at a significant distance from a well. Tracers and hydraulic tests using packers to isolate fractures are the best techniques in present use for determining fracture continuity.

FRACTURE CHARACTER

The apparent width of fractures, roughness of the faces, and volume and type of filling material are very important to the evaluation of fractures as conduits for geothermal fluids. Based on laminar flow, the permeability of a smooth fracture is proportional to the square of the aperture or width. Permeability also is a function of wall roughness, or fracture fillings. There are several acoustic and mechanical logs that may provide a measurement of apparent fracture width at the wall of the borehole. A series of four acoustic televiewer logs of a fracture zone in gabbro at Chalk River, Canada, is shown in figure 1. The first logs made of this fracture zone indicated that it was quite open and likely to have significant permeability. Packer tests indicated a very rapid decrease in flow probably due to the effect of a nearby boundary. The series of televiewer logs in figure 1 were made at different signal gain in order to develop a three-dimensional picture of the intersecting fractures. Note that the steepest fracture, dipping to the northeast, appears almost closed at the greatest gain where the signal is being reflected from more distant surfaces of the openings. The lower-angle fracture still shows some open area, but much of it is closed off by selvedges of rock or material filling the fracture.

One of the problems with fracture logging with devices that have a shallow radius of investigation is that the process of drilling and fluid circulation tends to change the character of fractures near a borehole. The width of a fracture can only be measured with some degree of accuracy where it is nearly perpendicular to the borehole wall. Areas where an acute angle is formed between the borehole wall and the plane of a steeply dipping fracture generally are broken out during drilling. This phenomenon can be observed in both cores and in the wall of a borehole. Examples of this are seen at the top and bottom of the sinusoidal fracture intersections in figures 1 and 5. Even where the intersection of a fracture and a drill hole are not artificially widened, circulation of drilling fluids can wash out clay or other soft material that may be plugging natural fractures. Conversely, drilling mud may plug otherwise permeable fractures. In the Raft River geothermal reservoir, acoustic-televiewer logs were made across a permeable fracture zone before and after the circulation of bentonite drilling mud (Keys and Sullivan, 1979). The televiewer logs clearly show plugging of the fractures by bentonite.

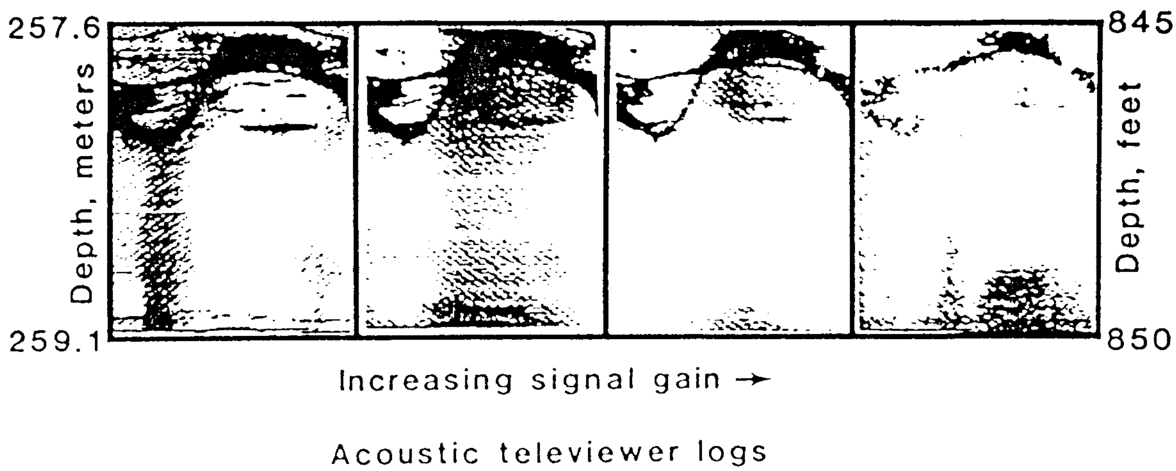

Figure 1. Acoustic televiewer logs of intersecting fractures in igneous rocks, Chalk River, Canada.

Fractures that are completely filled with minerals, such as quartz or calcite, cannot be detected by any equipment that will function in a hot well. However, such fractures will not transmit much water. Fractures that are partly closed by crystals or that have very rough surfaces rarely are distinguished from completely open fractures yet this is an important factor in determining permeability. Clay-filled fractures may be detected by acoustic, resistivity, or nuclear logs if those properties of the clay contrasts with the host rocks. At present there is no way to identify the type of clay or to determine the volume of filling.

RELATIONSHIP OF FRACTURES TO LITHOLOGY AND ALTERATION

There is evidence in a number of geothermal areas that the distribution of fractures and probably their productivity is related to lithology. Contacts between different rock types may be particularly favorable for productive fractures. Some of these fracture zones may actually be faults that cannot be recognized as such on geophysical logs. Competent rocks tend to be more fractured than softer rocks that can be deformed by plastic flow. In some instances, however, increased competence may be due to hydrothermal alteration and the products of that alteration may fill open fractures. An example of increased prevalence of fractures in a silicified zone was found at Raft River (Keys and Sullivan, 1979).

Hydrothermal alteration is a guide to permeable fractures in many areas, however, these may be "fossilized" conduits that are now plugged by minerals. Hydrothermal alteration can be of many types depending on the original composition of rocks, and the chemistry and temperature of the migrating fluids. The most common types determined in our logging to date are alteration of feldspars to clay or zeolites, alteration of biotite or muscovite to chlorite, and silicification. These and other types of alteration may produce changes that can be recognized on logs. Gamma-spectral data collected in several geothermal wells have indicated that potassium has migrated from the central areas of altered zones toward the margins where it is concentrated (Keys, 1979). Gamma-spectral data from drill holes in several igneous plutons also show that uranium migrates along permeable fractures so that their location may be indicated by uranium depletion or enrichment. West, Kintzinger, and Laughlin (1975) describe this application of gamma-spectral logs in the Los Alamos hot, dry-rock wells.

HYDRAULIC CONDUCTIVITY

Data on the permeability or hydraulic conductivity of fractures are most important yet difficult to obtain directly by geophysical measurements in boreholes. Flowmeter and temperature logs have been used to estimate the relative magnitude of permeability of fractures in geothermal wells (Keys and Sullivan, 1979; Schimschal, 1981). These techniques will be described later, however, it is important to note that either pumping or injecting water is necessary for semiquantitative results. Results obtained by isolating fractures with packers are more accurate, but much more expensive and time consuming. Analysis of acoustic-waveform data has provided attenuation factor that shows a good quantitative relationship to fracture permeabilities measured by hydraulic testing. However, the technique has not yet been tried in a geothermal well (Paillet, 1980).

BOREHOLE GEOPHYSICS PROVIDES FRACTURE DATA

Although a number of borehole-geophysical methods may provide data on the location and character of fractures on geothermal wells, they all have limitations. A comparison of the advantages and disadvantages of fracture-logging methods that have been used in geothermal wells is summarized in table 1.

In the limited space available in this paper it will be impossible to explain the principles of each of the logging techniques. Information on the application of the logging techniques to ground-water problems can be obtained from Keys and MacCary (1971). Handbooks provided by the major logging-service companies also explain the principles as applied to petroleum and should give the temperature rating of their tools. The state-of-the-art in geothermal well logging is summarized by Sanyal, Wells, and Bickman (1980), and Keys (1982). Developments in high-temperature logging equipment are summarized by Veneruso and Coquat (1979).

To improve log analysis in igneous rocks and to provide for log calibration for geothermal applications, the U.S. Department of Energy has recently completed three test pits at the Denver Federal Center (Mathews, 1980). Each of the pits is constructed of blocks of igneous rocks 2.4 m (meter) in diameter by 6 m deep. The rock types are a fine-grained and a coarse-grained granite, and a hydrothermally altered diorite. A number of laboratory measurements are being made on the core from the logging holes in each block. Because of the importance of fractures in geothermal production, artificial fractures at different angles and of different widths have been included in these blocks. These test pits are available for logging by anyone at no charge.

The hypothetical responses of five of the geophysical logs that are most useful in igneous and metamorphic rocks, the most common geothermal host rocks, are shown in figure 2. The response of logs to fractures cannot be separated from the response due to lithology and fracture-related hydrothermal alteration. The two fractures in the lithology column of figure 2 appear as they would on an acoustic-televiewer log. The low-angle fracture causes a response on all the geophysical logs, but the high-angle fracture may produce ambiguous anomalies at best. Both the caliper and acoustic-velocity logs incorrectly indicate the presence of several, rather than one high-angle fracture. The hypothetical rock sequence is

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Type of log	Operational status at 250°C	Fracture data obtained	Reliability of interpretation	Other considerations
Acoustic televiewer	Unreliable?	Location, apparent width, strike and dip	Very good	Probe must be centralized; heavy mud decreases signal.
Acoustic velocity	Unreliable?	Cycle skip at open fractures	Fair	Probe should be centralized.
Acoustic wave form	Unreliable	Amplitude anomalies indicate hydraulic aperture	Interpretation difficult	Centralize probe - need digitizing equipment.
Resistivity	Reliable	Less resistive anomalies at fractures	Ambiguous	Only short-spaced tools useful.
Dipmeter	Unreliable?	Same as above plus fracture orientation	Ambiguous - computer interpretation doubtful	Expensive log
Spontaneous potential	Reliable	Streaming potential; noise at producing fractures	Questionable	Affected by water-quality changes.
Temperature	Reliable	Change in gradient at permeable fractures	Very good but semiquantitative	Must be some water moving in the well.
Flowmeter	Unreliable?	Change in flow rate indicates fracture permeability	Need caliper log; semiquantitative	Pumping or injecting required.
Caliper	Reliable?	Larger hole diameter at fracture	Can be ambiguous	Difficult in deviated wells.
Neutron	Reliable	Greater porosity at open fractures	Fair at large fractures	Should be short-spaced and collimated.
Gamma-gamma	Reliable	Lesser bulk density at open fractures	Fair at large fractures	Should be short-spaced and collimated.
Gamma and gamma spectral	Reliable	Anomalies at open or closed fractures	Interpretation difficult	

Table 1. Borehole geophysical methods for evaluation of fractures in geothermal wells.

shown with silica content decreasing with depth. Experience has shown that, in general, basic rocks have less radioactivity, more apparent neutron porosity, greater acoustic velocity, and less resistivity than silicic rocks. Increasing content of micas, such as in schist, may increase radioactivity and apparent neutron porosity, and decrease acoustic velocity and resistivity. Superimposing altered and fractured intervals on this rock sequence greatly complicates log interpretation. Altered rocks generally are indicated by a larger diameter drill hole as are schists. Natural radioactivity may be either more or less in altered intervals. The migration of potassium toward the margins of one altered zone is shown on the gamma log in figure 2. Altered rocks usually are indicated by a much greater apparent neutron porosity, slower acoustic velocity, and less resistivity than the equivalent fresh rocks. Because the derivation of fracture data from geophysical logs is so complex, a short summary of each of the major types of logs follows.

Acoustic Logs

The acoustic-televiewer, acoustic-velocity, and acoustic-waveform logs probably are the most useful types of logs for providing information about fractures. The televiewer probe is the most complex and least reliable at high temperatures, but we have recorded logs at temperatures greater 260°C. This probe probably provides the least ambiguous information on fracture location, orientation, and character. An acoustic-televiewer log of a permeable fracture zone in igneous rocks in a production well at Roosevelt Hot Springs, Utah, is shown in figure 3. The zone consists of a major open fracture at the top and several relatively closed fractures in an altered zone below. Temperature logs indicate that this fracture zone is a major producer of hot water and steam. The orientation of the fractures can be measured directly from the log; the average dip is 44° to the southwest and the strike is approximately N25°W with respect to magnetic north.

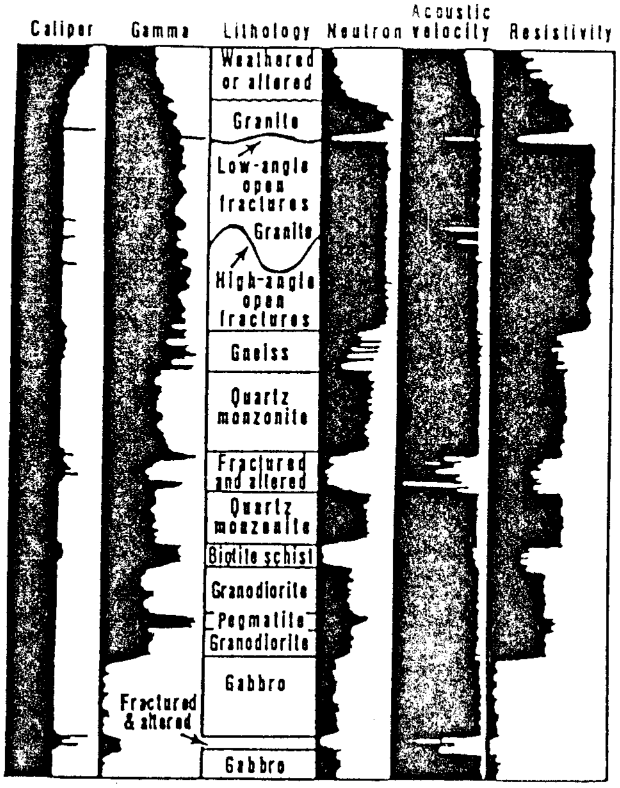

Figure 2.--Hypothetical responses of caliper, gamma, neutron, acoustic velocity, and resistivity logs to various types of igneous and metamorphic rocks.

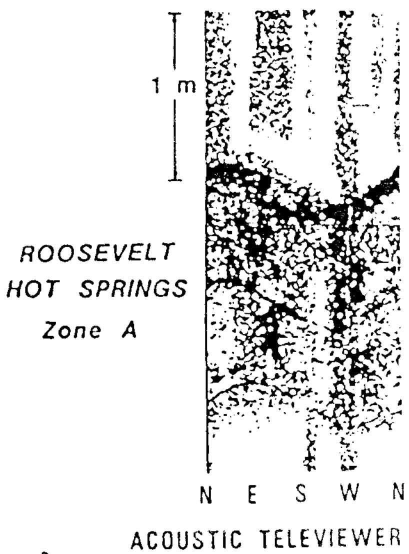

Figure 3. Acoustic-televiewer log of production zone A, Roosevelt Hot Springs, Utah.

The acoustic televiewer also can be used to record magnetically-oriented, hole-diameter information. Four oriented, acoustic-caliper traces across the same fracture zone seen in figure 3 are shown in figure 4. A mechanical-caliper log is shown for comparison. Note that the acoustic-caliper traces clearly define the uppermost open fracture and the fracture is deeper in the hole in

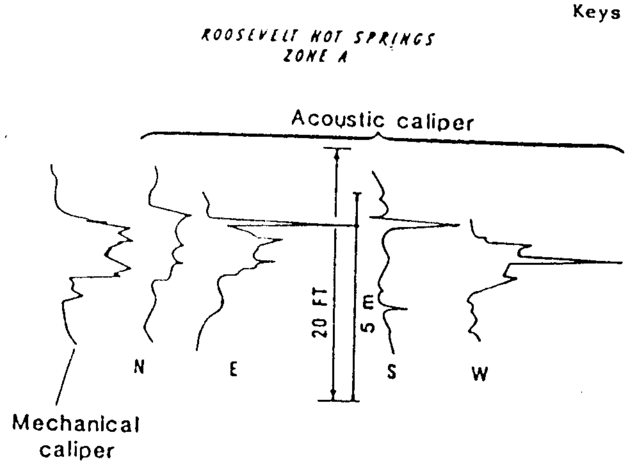

Figure 4. Mechanical- and acoustic-caliper logs, Roosevelt Hot Springs, Utah.

the west trace, which supports the general direction of dip seen on the televiewer log.

Although borehole television and borehole cameras using film have been used for fracture logging in low-temperature wells, apparently none have been developed for high-temperature logging. Borehole television also has some limitations in comparison with the acoustic televiewer. A detailed log of fractures in core from a hole drilled in igneous rocks along with borehole-television and acoustic-televiewer logs are shown in figure 5 (F. L. Paillet, U.S. Geological Survey, written commun., 1982). The first two sets of data were plotted in the same format as the televiewer for ease of comparison. Note that the television log shows the fewest fractures and that some tight fractures found in the core were missed by the televiewer.

Conventional acoustic-velocity logs usually show a cycle skip at an open fracture as demonstrated in figure 2. These cycle skips are caused by attenuation of the compression wave below the automatic triggering level. Therefore, the response is not uniquely caused by fractures, although cycle skips may be a fairly dependable indication of fractures in some holes. The amplitude of the trace deflection at a cycle skip is not indicative of the size of the fracture.

Paillet (1980) has shown that changes in amplitude of the tube-wave part of a digitized signal from a standard acoustic-velocity probe can provide useful fracture information in igneous rocks. He has demonstrated a quantitative relationship between the decrease in amplitude of the tube wave and the hydraulic conductivity or hydraulic aperture of fractures. The aperture data were calculated from isolation packer tests of individual fractures or sets of fractures. Although this technique has not been tried in geothermal wells, it should work if a lower frequency is generated to offset the effect of the larger diameter of geothermal wells and to transmit energy across wider fractures.

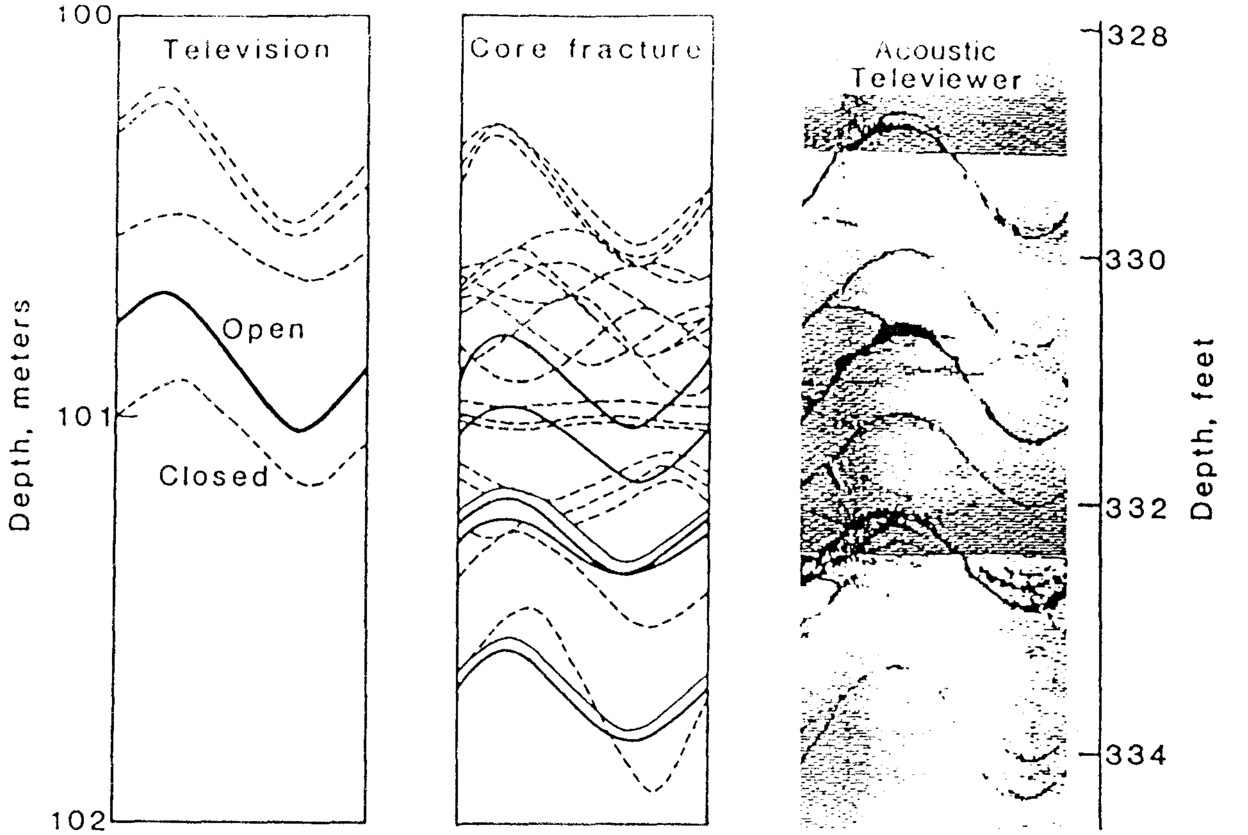

Figure 5. Comparison of fractures reconstructed from television and core data with acoustic-televiewer log, Whiteshell, Canada.

Compression and shear waves have been used to map hydraulic fractures at Los Alamos, New Mexico (Albright, and others, 1980). These waves have been transmitted between geothermal wells as much as 46 m apart in fractured granite. The character of the waveforms reportedly depends on the presence and number of fractures along the acoustic paths and on their pressure states. The authors also have demonstrated that the change in size of hydraulic fractures can be mapped acoustically. The waveform data were digitized from a stationary receiver in one well while the transmitter was moved in another well. The data were collected at hydrostatic pressures and at pressures sufficiently increased to separate fracture faces. When the fractures were pressurized, shear waves were not propagated and compression waves were attenuated significantly. The approximate location of a large hydraulically-induced fracture between the wells was mapped from the attenuation data.

Electric Logs

Short-spaced resistivity logs have sufficient resolution to produce anomalies of lower resistivity at small fractures if the resistivity contrast between the rock and fracture is sufficient and the fluid in the well is not too saline (fig. 2). The differential single-point resistance probe, short normal, and micro or short-focused systems have the best resolution for fractures. All the multielectrode configurations have the limitation that very thin layers, like fractures, may show a reversal. The single-point log does not show such reversals.

Dipmeter logs have been made by commercial companies in a number of geothermal wells in order to obtain information on fractures. Several comparisons have been made between acoustic-televiewer logs and dipmeter logs in order to evaluate the latter. The analog traces on a dipmeter log in igneous rocks do show the location of most major fractures and strike and dip can be calculated. However, it is extremely difficult to interpret a complex fracture system on the oriented dipmeter traces. Computer programs written to provide a printout of fracture information from commercial dipmeter logs can be misleading in complex systems. A typical complex system of intersecting, relatively tight fractures in a geothermal well in Long Valley, California, is shown in figure 6. A complete set of conventional commercial logs was made in this well, but none, including a high-resolution dipmeter log, responded to this fracture system. The fracture in the upper one-half of the figure is nearly vertical and it is intersected by two sets of lower-angle fractures.

An acoustic-televiewer log of an apparently open fracture, or two parallel fractures, in a geothermal exploration well drilled in basalts, tuffs, and rhyodacite at the Idaho National Engineering Laboratory is shown in figure 7 (Doherty and others, 1979). This major fracture,

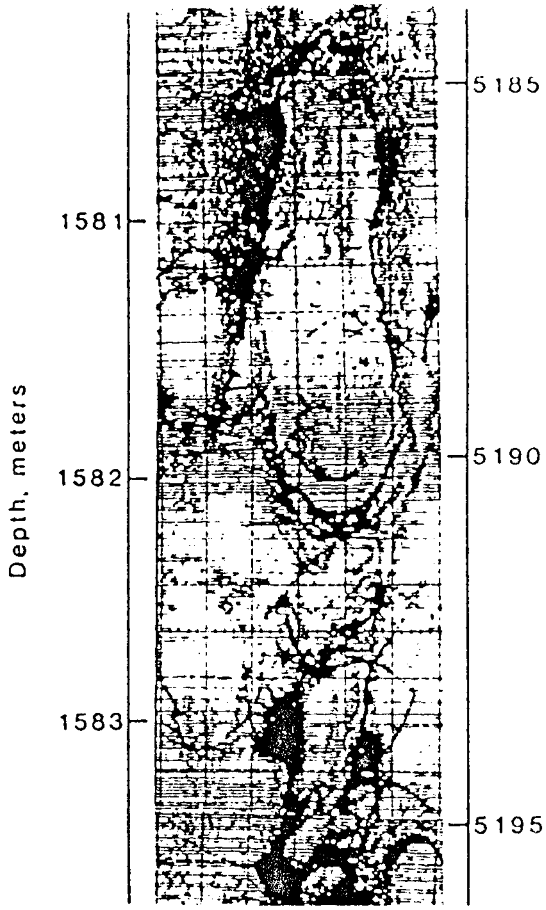

Figure 6. Acoustic televiewer log of a complex fracture system, Long Valley, California.

which dips approximately 70° to the northwest, produced anomalies on most of the commercial logs made in the well. A comparison of the dipmeter, caliper, gamma, acoustic-velocity, neutron, and gamma-gamma logs to the televiewer log is shown in figure 7. The fracture is clearly distinguished on all of the logs yet it apparently produced very little hot water. A temperature log (not shown in fig. 7) showed a very small anomaly that indicated that some water is moving through the fracture. The dipmeter log did not respond consistently to the wide variety of fractures penetrated by this well.

Nuclear Logs

All nuclear logs: gamma, gamma-gamma, and neutron may respond to large fractures that are open near the borehole, like those in figures 3 and 7. In contrast, none of the nuclear logs, except gamma under certain conditions, will respond to smaller fractures like those in figure 5. This lack of resolution is due to the averaging effect due to the relatively large volume of investigation of nuclear probes. The volume of investigation, which is large in relation to small fractures, can be shortened vertically by collimation added to the probes or by shortening the spacing between source and detectors. The angle of dip of a fracture also is an important factor with respect to detection by nuclear probes. High-angle fractures contribute to the average probe response within a longer depth interval and are thus not detected.

Gamma logs may show fractures to be either more or less radioactive than the surrounding rocks (figs. 2 and 7). This change usually is due to either leaching or precipitation of uranium and its decay products, and they can be identified by gamma-spectral logging. Relatively

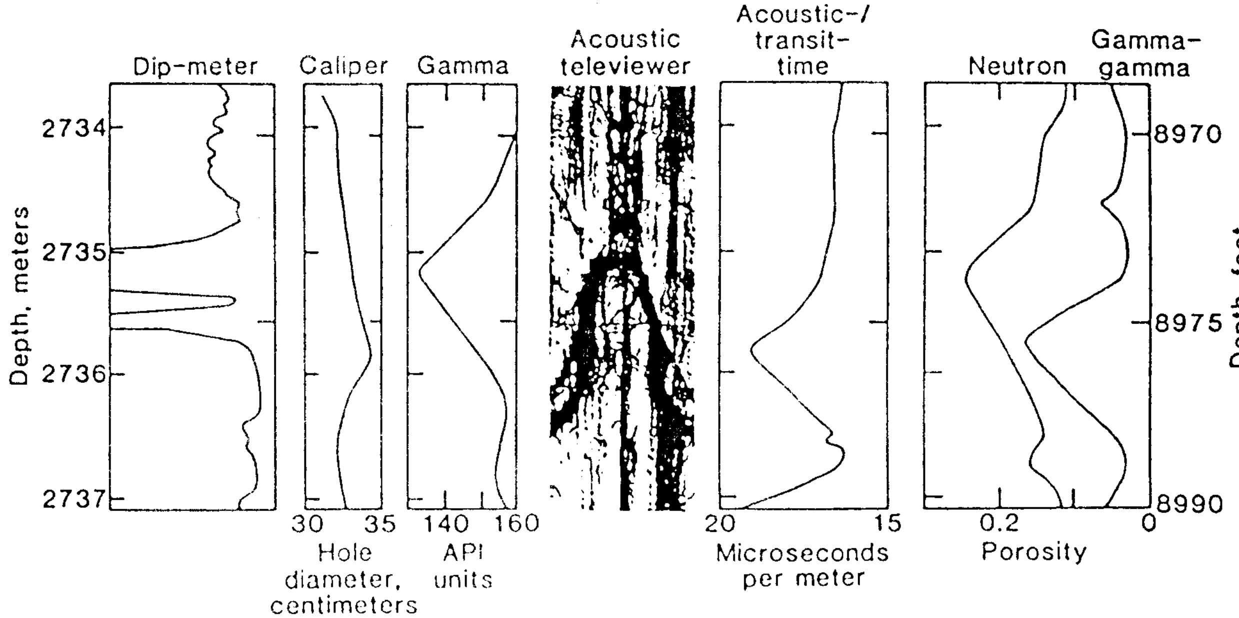

Figure 7. Dipmeter, caliper, gamma, acoustic televiewer, acoustic transit-time, neutron, and gamma-gamma logs of well INEL No. 1, Idaho National Engineering Laboratory.

large concentrations of radon have been found in some geothermal fluids and emission of this gas from a fracture may be detected by gamma logging. Nelson, Rachiele, and Smith (1980) describe the use of gamma logs to measure rates of water flow in drill holes at Stripa, Sweden. The radon and water are flowing from fractures in granitic rock that has a relatively large content of uranium and thorium. Radon-222 does not emit gamma radiation so it is detected indirectly by the presence of gamma-emitting decay products, lead-214, and bismuth-214.

Standard gamma-gamma (density) probes may detect large fractures with minimal dip because of the decrease in bulk density in the volume investigated (fig. 7). Short-spaced, high-resolution, gamma-gamma probes, like some used for coal logging, may detect smaller fractures.

Neutron probes detect fractures due to the increase in porosity. Neutron logs have provided better results than gamma-gamma logs in igneous rocks for two possible reasons. First, the response of a neutron log is nonlinear and reaches a maximum in rocks with minimal porosity. Second, alteration along fractures may produce hydrated minerals that add to the neutron anomaly produced by the fracture. We are testing a new type of compensated-neutron probe that uses a number of different detectors. Several of the very short-spaced detectors have been found to be quite sensitive to fractures in igneous rocks.

Caliper Logs

Most fractures that are capable of transmitting significant quantities of water or steam can be detected by a high-resolution caliper probe and apparent fracture width may be estimated. The most sensitive probes use three or four arms about the diameter of a pencil. Calipers with four independent arms that are magnetically oriented can provide information about the strike and dip of fractures. This kind of caliper probe also eliminates the ambiguities seen on average hole-diameter logs of steeply dipping fractures (fig. 2). Commercial caliper logs made with larger arms, pads or bow springs, lack the resolution necessary to detect any but the largest fractures. Caliper logs of any type are essential to avoid the common incorrect interpretation of all types of logs that may be due to hole-diameter effect. Changes in average hole diameter also may indicate alteration or contacts between different rock types.

Temperature and Flow Logs

Temperature logs usually are made in geothermal wells, and they occasionally are used to detect permeable fractures or to estimate the relative magnitude of permeability (Syms and Syms, 1981). Keys and Sullivan (1979) used temperature and flowmeter logs of a geothermal production well at Raft River, Idaho, to estimate the relative contribution from several fracture zones. The logs were made with the well both flowing and shut in. More recently Schimschal (1981) used the same equipment to make impeller flowmeter logs of a well during an injection test at Raft River. Both stationary and trolling measurements were recorded digitally while water was injected at a rate of 1,710 liters per minute. A computer program was used to correct for changes in hole diameter, logging speed, and impeller revolutions. Computer plots of hole diameter, flowmeter revolutions for upward logging, calculated flow volume and apparent hydraulic conductivity are shown in figure 8.

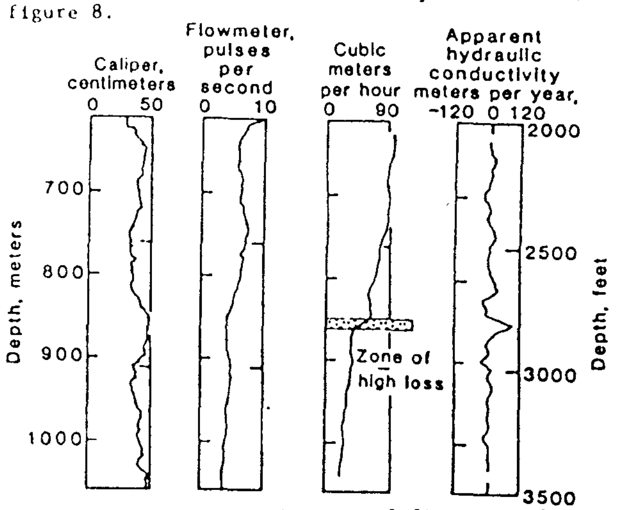

Figure 8. Computer reduction of flowmeter data from Well No. 7, Raft River, Idaho (Schimschal, 1981).

Most impeller flowmeters are not capable of making measurements at in-hole flow velocities less than 1.2 to 1.5 meters per minute. The flowmeter is, therefore, usually not sensitive enough to detect small flows from fractures in large-diameter geothermal wells. In contrast temperature logs can detect very slow flow rates. Although quantitative analysis of the data is more difficult, the temperature anomaly at the major fracture in figure 7 is a sharp offset of approximately 0.1°C in an otherwise uniform gradient. The scales on most temperature logs made by commercial companies are not expanded sufficiently to detect anomalies smaller than this. We have found that temperature anomalies of a few hundreths of a degree Celsius may indicate an interval of water entry or loss in a well.

High-Temperature Logging Equipment

The state-of-the-art in logging equipment that will operate in geothermal wells is summarized by Veneruso and Coquat (1979) and Keys (1982). Although logging probes available for sale or service are advertised to operate at 250°C, reliability has not been satisfactory. Problems with logging cables, cable heads, and seals have decreased logging capability at temperatures higher than 250°C. Although it is possible, but expensive, to cool some geothermal wells by circulating cold water, both temporary and permanent changes may be caused in the rock. Such changes are not well understood, and they may affect the response of acoustic or resistivity probes.

Even if logging equipment operates in a geothermal well, the data obtained may be less than accurate. Thermal drift in probe output is a common problem. Furthermore, few probes are designed for the very large diameter caused by caving of some geothermal wells, and logging systems are not set up to process the unusual data obtained from altered igneous and metamorphic host rocks. Sandstone, limestone, and dolomite are the only three matrix lithologies available on most service trucks for on-board plotting of porosity curves. It is not surprising, therefore, that porosity values on logs of many geothermal wells are found to have significant errors. The best way to increase the chance that logging equipment will work in a geothermal well and improve the quality of the logs obtained is to notify the logging company as far ahead of time as possible of the hole and geologic conditions anticipated. A knowledgeable log analyst on the job also can contribute to quality control of the data obtained.

CASE HISTORIES--FRACTURES IN GEOTHERMAL WELLS

Although most Earth scientists agree that fractures are the conduits for water movement in many geothermal reservoirs, direct evidence is not always available. In addition to temperature limitations of logging equipment, dry steam wells like those in the Geysers in California cannot be logged acoustically or electrically unless a water column can be maintained in the well. Even where logging of geothermal wells is possible, fracture-sensitive logs generally are not made. We have logged thousands of meters of geothermal wells in Imperial Valley and Long Valley, California; Raft River and INEL, Idaho; Marysville, Montana; Los Alamos, New Mexico; and Roosevelt Hot Springs, Utah. The main purpose of these studies was to improve the state-of-the art in geothermal logging equipment and log analysis with one of the goals being to learn more about fracture permeability. In each of these areas, except the Imperial Valley, borehole geophysics demonstrated that fracture flow was very important.

Complete suites of commercial company logs were made in almost every well on the Raft River reservoir, and a number of acoustic-televiewer logs also were made (Keys and Sullivan, 1979). There is overwhelming evidence that most production and permeability is due to relatively few open fractures. It is likely that enough data exists to construct a three-dimensional fracture model of the reservoir. The logs of a well at Roosevelt Hot Springs, Utah, made during a production test, likewise indicate that most of the significant flow is issuing from relatively few fractures. Even in relatively unproductive wells, the small flow still comes from a few partly open fractures. The difference between a "dry" hole and a production well may thus be due to intersecting one or more large open fractures. For these reasons a better understanding of fracture systems and how to measure their properties is justified.

HYDRAULIC FRACTURES

Los Alamos Scientific Laboratory has pioneered the concept of circulating water through artificial fractures in hot "dry" rocks (Albright and others, 1980). An acoustic-televiewer log of a hydraulic-induced fracture in Los Alamos Well EE-1 is shown in figure 9. The complex hydraulic fracture is parallel to the well bore. It crosses and is displaced by low-dip natural fractures between depths of 2,943 and 2,943.6 m. The hydraulic fracture also appears to cross a contact between two different types at a depth of 2,944.6 m. The fact that hydraulic fractures usually parallel the well and are more complex than most natural fractures make them difficult to measure with most borehole-geophysical methods. The acoustic televiewer is one method that can obtain useful data on hydraulic fractures in geothermal wells.

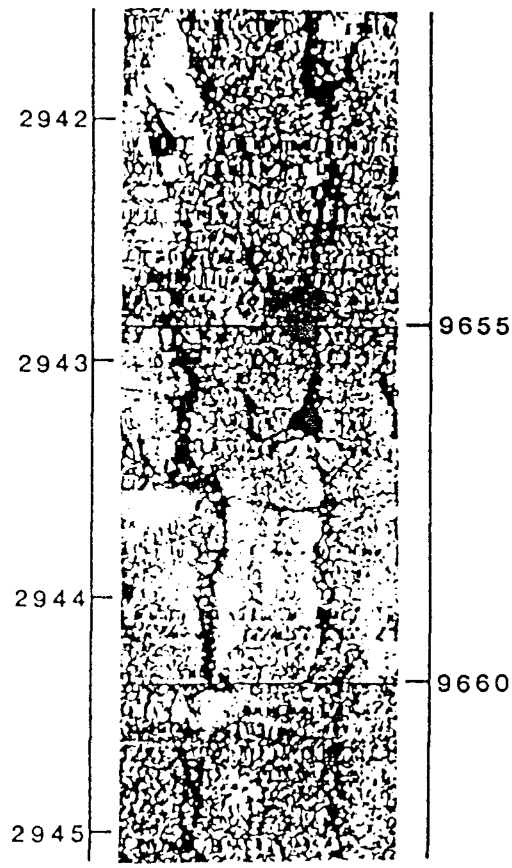

Figure 9. Hydraulically induced fracture intersecting two natural fractures and a lithologic contact, Well EE-1, Los Alamos, New Mexico.

Hydraulically fracturing also has been conducted in an attempt to increase the productivity of geothermal wells. Acoustic-televiewer logs were made before and after fracturing, and propping operations were conducted in two wells at Raft River, Idaho (Keys, 1980). In one well, a new hydraulic fracture was logged for a vertical distance of approximately 44 m. In the other well, a hydraulic fracture was logged for a vertical distance of 58 m, but it had been detected on a pre-fracture televiewer log. This fracture probably was due to the propping and extending of a fracture that was accidentally induced during drilling and testing. Accidental hydraulic fractures are being found in wells drilled for many purposes including geothermal energy. An irregular vertical fracture logged at Roosevelt Hot Springs is likely to have been accidentally induced during drilling.

Hydraulic fractures are produced at right angles to the existing direction of least principal stress. If the stress field is the same now that it was when the major natural fractures were produced, hydraulic fractures may parallel rather than intersect a major set of existing fractures (Wolff, and others, 1974). For this reason, it is quite important to obtain data on the orientation of both natural and artificially induced fractures.

SUMMARY

The importance of fractures to the development of geothermal energy is well established. Fractures also are important in characterizing sites for radioactive-waste disposal and in engineering geology related to dams and other large structures. Borehole geophysics can provide data on fractures intersected by drillholes, but techniques are needed for characterize fractures at some distance from these holes. Acoustic and electric methods seem to offer the most potential for additional research. Acoustic methods already have been demonstrated to provide information on fracture geometry and permeability and to permit mapping of fractures between wells. A continuation of tube-wave studies in a single borehole, and use of various parts of the acoustic spectrum between wells and the surface will undoubtedly improve our ability to understand fractures in the subsurface.

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