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**TOPICAL REPORT ON SUBSURFACE
FRACTURE MAPPING FROM GEOTHERMAL
WELLBORES**

Phase I: Pulsed Radar Techniques
Phase II: Conventional Logging Methods
Phase III: Magnetic Borehole Ranging

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D124-631
N713-28
SP-1

September 1980

Work Performed Under Contract No. AC04-79ET27013

H-Tech Laboratories, Inc.
Santa Monica, California

U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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PREPARED FOR THE
U.S. DEPARTMENT OF ENERGY
DIVISION OF GEOTHERMAL ENERGY
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ABSTRACT

To advance the state-of-the-art in Hot Dry Rock technology, an evaluation is made of (i) the use of radar to map far-field fractures, (ii) the use of more than twenty different conventional well logging tools to map borehole-fracture intercepts, and (iii) the use of magnetic dipole ranging to determine the relative positions of the injection well and the production well within the fractured zone. It is found that according to calculations, VHF backscatter radar has the potential for mapping fractures within a distance of 50 ± 20 meters from the wellbore. A new technique for improving fracture identification is presented. Analyses of extant data indicate that when used synergistically the (1) caliper, (2) resistivity dipmeter, (3) televiewer, (4) television, (5) impression packer, and (6) acoustic transmission are useful for mapping borehole-fracture intercepts. Improvements in both data interpretation techniques and high temperature operation are required. The surveying of one borehole from another appears feasible at ranges of up to 200 to 500 meters by using a low frequency magnetic field generated by a moderately strong dipole source (a solenoid) located in one borehole, a sensitive B field detector that traverses part of the second borehole, narrow band filtering, and special data inversion techniques.

SECTION 1

INTRODUCTION

This topical report is submitted under Contract DE-AC04-79ET27013 to assist in the planning of future experiments in the Hot Dry Rock program by providing a timely review of (i) the use of radar to map far-field fractures, (ii) the use of conventional well logging tools to map borehole-fracture intercepts, and (iii) the use of magnetic dipole ranging to determine the relative positions of the injection well and production well within the fractured zone. Each topic is examined in some detail. The emphasis in the radar study and the magnetic ranging study is on basic physics, while that of the logging study is on experimental data analysis and interpretation. Important recommendations are made for the better utilization of each technique.

1.1 THE MAPPING OF FRACTURES IN A GEOTHERMAL RESERVOIR BY PULSED RADAR

The widespread use of radar in the everyday world to perform detection, tracking and mapping functions, and some recent experiments underground to explore salt domes /1,2/ and coal mines /3/, and to locate buried objects /4,5/ makes it quite natural to inquire as to whether or not radar can be used in a geothermal reservoir to detect and map the fractures which are so crucial to the operation of a hot dry rock system. The basic operating principles of the above ground and subterranean radars are essentially similar. However, the constitutive properties of the medium, the nature of the radar target, and the borehole geometry introduce physical constraints and technical problems into the design of a subterranean system that are quite different from those of an above ground system. The two most important issues regarding the usefulness of a fracture mapping radar are those of operating range, and the identifying and locating of a fracture. It is shown in this report that according to calculations, the maximum useful range of a backscatter radar in a granitic medium is of the order of 40 meters. However, more than just a long range is required; prior to hydraulic fracturing, it would be useful to know the location

of naturally occurring fractures, but the identification of radar signatures from far-field fractures that do not intersect the borehole is an unresolved problem as is that of separating the signature of a fracture from that of a dielectric or conductive anomaly. On the other hand, fractures that are useful for transferring heat must intersect the borehole, and for this very important class of fractures a positive identification and ranging technique has been devised under this contract: By inflating the fracture with an electrically conducting fluid, say 0.5 molal NaCl, a large dielectric and conductivity contrast is created which greatly increases the strength of the return signal for frequencies in the range of 10^7 to 3×10^8 Hz. These frequencies are quite low compared to those sometimes proposed for fracture detection, but yield a stronger return signal than the higher frequencies for far-field fractures that are 1 to 2 mm in thickness. It is the relatively low frequency that allows the radar to see as far as 40 meters and the high conductivity that reflects waves with wavelength much greater than the fracture thickness. To be truly useful, a backscatter radar must resolve the angular position of a fracture, a task requiring the development of a directive antenna that will fit within the confines of a borehole. Recent experimental efforts have addressed this problem and some success has been claimed /6,7/, although the resolution does not approach that of an above ground antenna. Some theoretical designs for directive borehole antennas have been discussed in the literature /8/. If the radar is operated with the transmitter and receiver in separate boreholes that straddle the fracture, then the directivity requirements can be relaxed. (In this mode the range is at least twice as great as the backscatter range, which is the range normally quoted in this report.)

The operating range of subterranean radar is analyzed in Section 2. Three different models are used both to bound the problem and to indicate the increase in range that could be obtained by improving antenna performance. Fracture identification is discussed in Section 3, and the use of saline water injection for mapping fractures that intersect the borehole is quantified. Certain aspects of the physics used in Sections 2 and 3

are discussed as needed. These details include electromagnetic propagation in a conductive medium, the conductivity of granitic materials, Rayleigh's criterion, Fresnel's equations, receiver sensitivity, antenna characteristics, temperature effects, the minimum range of a radar, and pulse length. A summary of the radar study is presented in Section 4. The state-of-the-art of radar experimentation and radar hardware is reviewed in Section 8.

1.2 THE MAPPING OF BOREHOLE-FRACTURE INTERCEPTS IN A GEOTHERMAL RESERVOIR USING CONVENTIONAL LOGGING TOOLS

The availability of a large number of well logging tools, developed primarily for characterizing oil and gas bearing sedimentary strata, provides the opportunity to test and evaluate various concepts for detecting fractures in a geothermal well. Because the tools, which we shall call conventional tools, are ready for field use, invoke a wide range of physical phenomena, and have been refined and made more reliable over a span of years, it is wise both from an engineering and economic standpoint to test them in the hot dry rock program. In Section 5, more than twenty tools are evaluated for their ability to accurately map natural fractures, hydraulic fractures, and interwell flow connections. The basis for the evaluation is mainly experimental in nature. It is found that no one tool is able to accurately and unambiguously locate natural fractures. Eight techniques are identified which when used synergistically do a credible job of mapping natural fractures. Three additional methods are quite useful for determining the size and location of hydraulic fractures and interwell connections. The other techniques are of marginal value, although with additional development, one of them might prove useful. In Section 6, the data on natural fractures and weakness planes, obtained from the conventional logs, are used to develop a fracture model of the Fenton Hill reservoir which has proven useful in a global sense for setting ideas about the structure of the hot dry rock reservoir and in a detailed sense for interpreting microseismic data and investigating the performance of backscatter radar. A summary of the work on conventional tools is presented in Section 7. The use of conventional tools in fracture mapping activities in the United States, Canada, and Sweden is reviewed in Section 8.

1.3 DETERMINING THE RELATIVE POSITIONS OF TWO BOREHOLES USING MAGNETIC RANGING TECHNIQUES

The accurate alignment of the injection well, the production well, and the fracture zones, all at great depths in a hot dry rock reservoir, places stringent demands upon conventional wellbore surveying techniques. Experience has shown that as deviations from a straight line build up in a wellbore so do the cumulative errors in measuring the position of the wellbore with a gyroscopic tool. Efforts to map the relative positions of wellbores at depth have resulted in large uncertainties. To look for a remedy to this situation, we examine, in Section 9, the possibility of surveying one wellbore from a second wellbore using magnetic techniques. The main idea of magnetic borehole ranging is that by placing a magnetic dipole of known source strength (a solenoid) in one borehole and by measuring the vector components and the phase of the a.c. magnetic field in a distant borehole, both the range and the orientation of one borehole with respect to another can be determined. It is found that by using a low frequency magnetic field with $2 < f < 100$ Hz, a sensitive B field detector, a moderately strong dipole source with a magnetic moment of 10^4 to 10^5 A-m², and narrow band filtering, ranges of between 200 to 500 meters appear viable. In our opinion, quite an effort would have to be made to get a reliable system into the field.

SECTION 2

RADAR PROBING DISTANCE

The range of an aboveground radar is measured in kilometers, that of a subterranean radar in meters. The thousand-fold reduction in range is caused principally by dissipation in the lossy geologic medium. Therefore, it is worthwhile to examine the effects of losses alone, unencumbered by problems of antenna design and fracture reflectivity, in order to place an upper bound on the maximum useful range that can be attained underground. Once this is accomplished, the extent to which the antenna radiation pattern and fracture reflectivity reduce the range can be clearly seen. That this is a profitable approach is borne out by the results themselves. For example, at 100 MHz, a hypothetical backscatter radar set that produces a perfectly collimated beam has a range of 56 meters. With a quarter-wave dipole antenna, which has rather poor directivity, the range is reduced by a factor of 1.7 to 33 meters. If it were possible to build a high gain antenna which would fit into a practical sonde (and such an antenna does not now exist), then the range would be reduced from the perfect case by a factor of only 1.3 to 42 meters. Thus, the upper bound is sufficiently close to what might be achieved in practice that it does indeed provide a useful estimate. Furthermore, the highly directive antenna provides a 27-percent increase in range over that of a simple dipole so that the effort to produce such an antenna is worthwhile, but not crucial in terms of range. (In terms of direction-finding capabilities in the backscatter mode, a narrow beam antenna is essential.)

2.1 UPPER BOUND RANGE MODEL

It is clear that the greatest range attainable by a radar would occur with a hypothetical beam with zero divergence and a target with perfect reflectivity. The range limitation for a given transmitter and receiver is then fixed solely by dissipation in the medium, and the situation is entirely analogous to the propagation of plane waves in a conductive medium. To proceed, we write Maxwell's equation in the form of the wave equation for the electromagnetic field as

$$\nabla^2 \vec{E} - \epsilon\mu \frac{\partial^2 \vec{E}}{\partial t^2} - \mu\sigma \frac{\partial \vec{E}}{\partial t} = 0 \quad (2.1)$$

and seek plane wave solutions for the electric field in the form

$$\vec{E} = E_1 e^{-i\omega t + \vec{\gamma} \cdot \vec{r}} + E_2 e^{-i\omega t - \vec{\gamma} \cdot \vec{r}} \quad (2.2)$$

where the constitutive properties of the medium are represented by σ , the conductivity, ϵ , the permittivity, and μ , the permeability, all of which may be functions of frequency, temperature and pressure. Implicit in this formulation of the constitutive properties is that the losses arise from currents controlled by the conductivity and driven by the electric field. An alternate description is often employed for dielectrics in which the permittivity is assumed to be a complex quantity and the conductivity is effectively replaced by the imaginary part of the permittivity. A second source of loss (and range reduction) is associated with the oscillation of magnetic dipoles in ferromagnetic materials, such as magnetite. To include magnetic losses, the permeability should be treated as a complex quantity. We have chosen not to do so because extant data for geologic media do not consistently separate the effects of electric and magnetic losses. To continue,

$$\gamma^2 = \mu\epsilon\omega^2 + i\sigma\mu\omega.$$

For convenience, we set

$$\gamma = \alpha + i\beta,$$

and solving for the attenuation factor, α (which is always a positive quantity), and the phase constant, β , we obtain

$$\alpha = \omega \left[\frac{\mu\epsilon}{2} \left(\sqrt{1 + \left(\frac{\sigma}{\epsilon\omega} \right)^2} - 1 \right) \right]^{1/2}, \quad (2.3a)$$

$$\beta = \omega \left[\frac{\mu\epsilon}{2} \left(\sqrt{1 + \left(\frac{\sigma}{\epsilon\omega} \right)^2} + 1 \right) \right]^{1/2}. \quad (2.3b)$$

The phase velocity is given by

$$c = \frac{\omega}{\beta} = \frac{c_0}{\sqrt{\kappa_e \kappa_m}} \left[\frac{2}{\sqrt{1 + \left(\frac{\sigma}{\epsilon\omega}\right)^2} + 1} \right]^{1/2}, \quad (2.3c)$$

where the specific inductive capacity, κ_e , is the ratio of the permittivity of the medium to that of vacuum (ϵ/ϵ_0), the specific magnetic permeability, κ_m , is the ratio of the permeability of the medium to that of vacuum (μ/μ_0), and c_0 is the speed of light in vacuum ($\approx 3 \times 10^8$ m/s). All three quantities, α , β , and c , are controlled by $\sigma/\epsilon\omega$, which is called the loss tangent. From Maxwell's equation, it is seen that the loss tangent is the ratio of dissipative currents to the vacuum displacement current. Two limiting cases are usually discussed / 9/.

Case I: $(\sigma/\epsilon\omega)^2 \ll 1$. The medium is either only slightly dissipative or the frequency is very high. By expanding α , β , and c in powers of $(\sigma/\epsilon\omega)^2$, the expressions are simplified to yield

$$\alpha = \frac{\sigma}{2} \sqrt{\frac{\mu}{\epsilon}} = 188.3\sigma \sqrt{\frac{\kappa_m}{\kappa_e}}$$

$$\beta = \omega \sqrt{\mu\epsilon} \left[1 + \frac{1}{8} \left(\frac{\sigma}{\epsilon\omega}\right)^2 + \dots \right]$$

$$c = c_0 / \sqrt{\kappa_m \kappa_e}.$$

The wave is dispersive, i.e., c depends upon ω , insofar as the constitutive properties are frequency dependent. The spatial attenuation rate is frequency dependent only through the constitutive properties.

Case II: $(\sigma/\epsilon\omega)^2 \gg 1$. The medium is either highly conductive (a metal) or the frequency is low (the situation more commonly studied in geophysical surveying of large areas). In this case

$$\alpha = \beta = \sqrt{\frac{\mu\sigma\omega}{2}} = \frac{1}{\delta} ,$$

$$c = \sqrt{\frac{2\omega}{\mu\sigma}} ,$$

where δ is defined as the skin depth. The wave is dispersive as shown by the expression for the phase velocity. The spatial attenuation rate is explicitly dependent upon frequency, increasing with the square root of the frequency, and is implicitly dependent upon the frequency through the conductivity and permeability.

Because of the great difference in electromagnetic behavior between Case I and Case II, it is worthwhile to determine if the granitic medium at radar frequencies acts either as a low-loss dielectric or as a good conductor. The characterization is done in terms of the loss tangent. For $\sigma/\epsilon\omega < 0.1$, the medium acts as a low-loss dielectric, while for $\sigma/\epsilon\omega > 10$, the medium acts as a good conductor. Using laboratory data for the conductivity of granite [3,10-15] and for the permittivity [11-15], the loss tangent is plotted as a function of frequency in Figure 2.1. It is important to bear in mind that the data were obtained from small samples at room temperature and atmospheric pressure and that in situ values in a geothermal reservoir may be different. Using the extant data, we find that at frequencies greater than 2.5×10^7 Hz, wet granite behaves as a low-loss dielectric. Note that for $f \gtrsim 10^8$ Hz, the loss tangent of wet granite is a very slowly decreasing function of frequency and has an average value of 0.045. Thus, the attenuation factor increases directly with frequency, i.e., $\alpha \doteq 1.15 \times 10^{-9} f$, where α is in nepers/meter and f is in Hz.

2.1.1 The Electrical Conductivity of Granite

The conductivity of granite has such a strong effect on radar performance (as shown in Subsections 2.2-2.4) that it is worthwhile to dwell on the subject at greater length. The conductivity data used to plot the loss tangent of wet granite in Figure 2.1 are themselves plotted in Figure 2.2, along with data for dry granite. Three concerns that arise when examining the data are addressed in this section; namely, the scatter in the data, the

Figure 2.1 Loss tangent vs. frequency with conductivity as a parameter. The specific inductive capacity, $\kappa_e = 6$.

Figure 2.2. The conductivity of granite as a function of frequency, measured in the laboratory. Wet granite: $\blacktriangle$ Ref. 3, $\bullet$ Ref. 10, $\blacksquare$ Ref. 14 (Fenton Hill). Dry granite: $\triangle$ Ref. 3, ∇ Ref. 11 (1 Westerly, RI, 2 Llano, TX, 3 Rockport, MA), $\times$ Ref. 12 (black & white), $+$ Ref. 12 (rusty), $*$ Ref. 12 (Raymond), $\diamond$ Ref. 13 (Cold Spring granite), $\square$ Ref. 14 (Fenton Hill), $\circ$ Ref. 14 (1 Westerly, RI, 2 Berkeley).

accuracy with which the laboratory data represents in situ properties, and trends in the data.

Most of the data are plotted in such a way that the scatter arises from genuine differences in constitutive properties between granites from different locations. This is particularly true of the dry granite data from References 11 and 12. Thus, the performance of radar in dry granite would be expected to vary from site to site. A second type of data scatter has been averaged out in most cases and only one datum is plotted for each type of granite at each discrete frequency. This scatter arises from the use of laboratory-size samples which are small compared to the scale of inhomogeneities in naturally occurring granites. Hence, different samples from what is nominally the same piece of granite may have different properties. The effect is quite striking, for example, in waveguide tests where the measured value of the conductivity often depends upon whether the arbitrarily designated front or back surface of the test specimen faces the incident wave. The magnitude of the scatter from sample to sample for specimens extracted from the same location is illustrated by the data plotted from Reference 14. These data are of particular interest to the geothermal program because they were obtained with samples removed from the hot dry rock wellbores at Fenton Hill. The scatter in the data is fairly large, amounting to a factor of nearly three from the lowest to the highest values at X-band (8 to 9 GHz). From what little data are available on repetitive runs on the same sample, it appears that the measurements were made to a precision of about 10 percent. The factor of three scatter thus appears to be the result of geologic variations.

Complete details of experimental procedures were not reported by the experimentalists, so it is not possible to assess the relative accuracy of the measurements. A brief review of the techniques is as follows: The data from Reference 3 were obtained on a Hewlett-Packard type 4815A impedance meter using small samples of gray granite and gneiss removed during construction of a vehicular tunnel in Switzerland. Measurements were made on dry samples which were in an "as received" condition and on wet samples which were prepared by soaking in tap water for an unspecified period of

time. As discussed below, we are concerned about the accuracy of the measurements for $f \geq 2.5 \times 10^7$ Hz. The data from Reference 10 were obtained at $10^3 \leq f \leq 10^5$ Hz using a standard Schering bridge technique (although important details of the sample holder were not revealed) and at $f = 9.15 \times 10^8$ and 2.45×10^9 Hz using a novel microwave heating technique. The low frequency data are not plotted in Figure 2.2, but rather are used as a basis for extrapolating the data to $f \geq 10^6$ Hz; thus, the straight line plot in Figure 2.2 is not a fit to the plotted points but rather is a means for comparing the high frequency and low frequency data. Samples of granite were obtained from a bedrock outcropping in north-central Georgia and for the wet measurements were soaked in a 1.0 N NaCl solution to provide a pore water with a known ionic concentration, even if that concentration were not representative of in situ values. The authors of Reference 10 believe that because of the high salinity their conductivity measurements at microwave frequencies are an order-of-magnitude greater than would occur in situ, but we note that the two data points plotted in Figure 2.2 are not far different from laboratory measurements made by other experimenters. Because of this relatively good agreement and because the high frequency lossiness of water is controlled more by the dipole moment of the water molecule than by ionic conduction, we believe that the data of Reference 11 are accurate to within a factor of two, rather than ten. The data from Reference 11 were obtained using well-established techniques /16/. At 4.5×10^8 Hz, a reentrant cavity forming part of a resonant circuit was employed. At 3.5×10^{10} Hz, voltage standing wave ratio measurements were made on a waveguide with a section loaded with granite and followed by a moveable short. Dry samples were employed from Westerly, Rhode Island, Llano, Texas, and Rockport, Massachusetts. The data from Reference 12 were obtained with samples of black and white, rusty, and Raymond granite. The data from Reference 13 were obtained with Cold Spring granite. Neither of these last two references contained details of the measurement techniques. The data from Reference 14 were obtained with samples extracted from wellbores EE-1

and GT-2 at Fenton Hill, with control samples of Westerly and Berkeley granite. Measurements were made of the voltage standing wave ratio using a granite-loaded short circuited waveguide with a slotted line.

The wet data have been fit by a curve as indicated in Figure 2.2, and this fit has been used in subsequent calculations to describe the conductivity of granite as a function of frequency. A curve has not been fit to the dry data, but the extrapolation of the low frequency data does provide a fair approximation to the high frequency dry data. The conductivity of wet rock is not much different from that of dry rock at frequencies greater than 1 GHz, but at low frequencies the wet rock is considerably lossier than dry rock. Qualitatively, most of the data appears to have the proper trend. One exception is the wet data from Reference 3, which indicates that the conductivity of wet granite approaches a constant value for $f \geq 2.5 \times 10^7$ Hz. This behavior is hard to reconcile with all of the other data and with the behavior of the components of wet granite, i.e., the conductivity of dry granite is an increasing function of frequency, Figure 2.2, as is that of water /16/. The roll-off in conductivity would be significant if it actually occurred because it would allow a greater maximum radar range than if the conductivity continued to increase with frequency. For the reasons previously advanced, we have discounted the data from Reference 3 at $f \geq 2.5 \times 10^7$ Hz and have used instead the fit to the wet data as shown in Figure 2.2.

Laboratory measurements are needed on granite at elevated temperature and pressure. Measurements in distilled water at 25°C and 85°C show that the dielectric constant and conductivity is a function of both frequency and temperature. Measurements on pyroxene /17/ show that for this mineral the permittivity is a function of temperature at low frequency, but for temperatures less than 300°C, the permittivity approaches a constant value at $f = 10^6$ Hz. The loss tangent, on the other hand, is a strong function of temperature even at $f = 10^6$ Hz. Although pyroxene is rarely found as a constituent of granite (and is itself a complex mineral), it appears crucial that the effects of temperature (and pressure) on the dielectric

constant and conductivity of granite be measured. Thus, our main concern is not with the absolute accuracy of extant constitutive properties data, but that an entire body of information crucial to the operation of radar in a geothermal wellbore is nonexistent. Although it is often risky to predict in situ values from laboratory measurements, we believe that laboratory measurements of the electrical properties of granite at elevated temperature and pressure would increase the accuracy of estimates of radar performance.

2.2 THE RANGE OF A PERFECTLY COLLIMATED RADAR BEAM IN A GEOTHERMAL RESERVOIR

For a perfectly collimated beam and a perfect reflector, the relation between the radar range, R , the transmitter power, P_t , the minimum usable signal power at the receiver, P_r , and α follows directly from Equation 2.2,

$$\frac{P_r}{P_t} = e^{-4\alpha R}, \quad (2.4)$$

where α is given in nepers/meter by Equation 2.3b. In the engineering literature, the attenuation is usually expressed in decibels/meter so that

$$A_{\text{db/m}} = 8.686 \alpha .$$

The maximum range is expressed as

$$R = \frac{5.0}{A} \log_{10} \frac{P_t}{P_r} . \quad (2.5)$$

The transmitter peak power is set by considerations of size, power dissipation, cost, and the fact that the range increases only logarithmically with power. The minimum useful received power depends upon the noise generated external to the receiver and various aspects of receiver design. In a deep subterranean setting, the principal sources of noise at microwave frequencies will arise from the thermal oscillations of the molecules of the rock and from within the circuits of the receiver. The bandwidth, coupling losses and signal averaging techniques, all affect the minimum

power necessary to produce a useful output signal. The received thermal noise is given by

$$P_n = kT\Delta f$$

when k is Boltzmann's constant ($k = 1.38 \times 10^{-23}$ J/K), T is the effective temperature of the noise source, and Δf is the bandwidth of the receiver. Because the medium is lossy, all of the energy radiated by the transmitter is absorbed within the rock; thus, the medium is a black body at microwave frequencies and is characterized by its actual temperature. (Above ground the effective temperature depends upon the frequency and the inclination of the antenna and can vary between a few degrees Kelvin to several thousand degrees Kelvin.) The bandwidth must be wide enough to respond fully to the energy contained within one pulse, but once this is accomplished, making the bandwidth any wider causes the detected noise to increase in direct proportion to the bandwidth without any further increase in the signal. It turns out that the optimum bandwidth depends upon the transmitter pulse shape and the pass band characteristics of the intermediate frequency amplifier so that $0.5 < \Delta f\tau < 1.5$, where τ is the pulse length /18/. For our purposes, it is sufficient to assume that the bandwidth is equal to the inverse of the pulse length, i.e., $\Delta f\tau = 1$. The receiver noise figure is a measure of how much noise is added by the receiver itself and is defined as the ratio of the input signal-to-noise power ratio, S_i/N_i to the output signal-to-noise power ratio, S_o/N_o ,

$$F \equiv \frac{S_i/N_i}{S_o/N_o}.$$

It is readily shown that only the first few stages of a superheterodyne receiver contribute significantly to the noise, for in a cascaded amplifier the noise addition of successive stages is inversely proportional to the gain of the preceding stages /18/. Thus, based on our data for microwave frontends /19/, we chose $F = 2$ db for our calculations. As a rough estimation to actual practice, we have taken coupling losses and

signal averaging techniques, lumped them together, and state that a usable signal must be 2 db above the output noise level. Hence, the minimum useful signal in our model is

$$S = 2.5 kT/\tau ,$$

which gives a maximum range of

$$R = \frac{5.0}{A} \log_{10} \frac{P_t \tau}{2.5 kT} \quad (2.6)$$

This form of the range equation emphasizes two important points. First, it is the energy contained within a radar pulse rather than the peak transmitter power that is fundamental in determining the maximum range. Second, the higher the reservoir temperature, the shorter will be the range. The pulse length is set by the minimum range that is to be explored, i.e., the transmitter must be quiescent before a return echo can be detected. For $f \geq 10^8$ Hz, the minimum range has been selected as 2 meters, which gives a pulse length of 33 nsec for $\kappa_e = 6$. At lower frequencies, the minimum range must increase because even a solitary half-sine pulse has a relatively long duration, e.g., at $f = 10^7$ Hz, a half-sine monopulse has a width of 50 nsec, which gives a minimum range of 3.1 meters. The maximum range as a function of frequency and peak radiated power, subject to the previously discussed conditions, at a reservoir temperature of 280°C (550°K) is plotted in Figure 2.3. The decrease in range with increasing frequency, Figure 2.3, reflects the increase in conductivity with increasing frequency, Figure 2.2. The scatter in the conductivity data between individual samples taken from the same location /14/ leads to an uncertainty in the calculated range of approximately $\pm 40\%$. It is clear from the results of this sample model that radar can have a potentially useful range in a geothermal reservoir of the order of 10 to 100 meters, and hence it is worthwhile to proceed with the formulation of more accurate models.

Figure 2.3. Maximum radar range vs. frequency and peak transmitter power with $\Delta f \tau = 1$ and a reservoir temperature of 280°C (550°K). The receiver noise figure is 2 db. Losses and the detectability criterion add another 2 db to the minimum usable signal strength. Three cases are considered: (1) a perfectly collimated beam and a perfect specularly reflecting target, (2) a pencil beam and a perfect diffusely reflecting target ($1/R^2$ -law), (3) a dipole radiator and a perfect diffusely reflecting target ($1/R^3$ -law). The degree of uncertainty in the calculated results, arising from scatter of constitutive properties data, is of the same order as the spread between a perfect beam and a dipole radiator, i.e., ± 30 to $\pm 40\%$.

2.3 THE RANGE OF A NARROW BEAM RADAR ILLUMINATING A LARGE PLANAR FRACTURE

The analysis of Subsection 2.1 predicts a greater range than can be achieved in practice because it ignores the reduction of signal strength caused by the geometrical spreading of both the transmitted beam and the return wave. This defect is now remedied by estimating the maximum range of a radar set employing a relatively high gain antenna, e.g., one with a beam spread of less than one radian, illuminating a large planar fracture. On physical grounds, it is clear that for a relatively narrow beam incident on a target which is much greater in lateral extent than the beam itself, all of the transmitted power falls on the target, and it is the spreading of the return signal which is responsible for a $1/R^2$ diminution of power at the receiving antenna. This argument can be quantified either exactly by solving a boundary value problem or approximately by adapting a phenomenological theory of sea echoes originally proposed by Goldstein /20/. We adopt the latter approach which is sufficient for indicating the influence of antenna design and large planar fractures on radar range.

For the setup sketched in Figure 2.4, assume that the fracture plane is composed of a large number of independent scattering sites. The power incident on any one scatterer (the j^{th} scatterer) is

$$P_{ij} = \frac{G_t F^2(\theta, \phi, R_j) P_t \sigma_j}{4\pi R_j^2} .$$

The pattern propagation factor, F , is defined as the ratio of the amplitude of the electric field that exists under actual operating conditions at some point in the medium (specified by the coordinates θ, ϕ, R with respect to the electric axis of the antenna) to the amplitude of a hypothetical electrical field that would exist in free space if the antenna were directed at the point under observation. In symbols,

$$F \equiv \left| \frac{E}{E_0} \right| ,$$

Figure 2.4. Narrow beam antenna illuminating a large planar fracture. Special case with beam lying in the plane of the borehole and the normal to the fracture surface from the radar set.

where E is the actual electric field at the point under observation, and E_0 is the hypothetical field along the beam axis in free-space. Because of the importance of absorption, F is separated into two parts,

$$F = f(\theta, \phi) e^{-\alpha R} .$$

The antenna pattern function, $f(\theta, \phi)$, is defined as the ratio of the free-space electric or magnetic field strength in the direction (θ, ϕ) to the free-space field in the direction of maximum radiation

$$f(\theta, \phi) \equiv \frac{E(\theta, \phi)}{E_0} \leq 1 .$$

The antenna gain for transmission, G_t , is defined as the ratio of the power radiated by an isotropic antenna, P_1 , necessary to produce a given field strength or Poynting vector, S_1 , at some given distance to the power radiated by a directional antenna, P_2 , producing the same field strength or Poynting vector at the same distance in the direction of maximum transmission. Thus,

$$G \equiv \frac{P_1}{P_2} = \frac{S_1 \int_0^{4\pi} d\Omega}{S_1 \int_0^{4\pi} |f(\theta, \phi)|^2 d\Omega} = \frac{4\pi}{\int_0^{4\pi} |f(\theta, \phi)|^2 d\Omega}$$

The antenna gain depends only on the pattern function. P_1 is the value of the transmitter power, which is assumed here to have a constant value for the duration of one pulse. The cross section of a scatterer σ_j is defined for a linearly polarized wave as the area intercepting that amount of power which, when scattered isotropically, produces a return signal equal to that observed from the target. Symbolically,

$$\bar{S}_r = \frac{\bar{S}_1 \sigma}{4\pi R^2} ,$$

where $\bar{S}_r$ and $\bar{S}_i$ are the average values of the Poynting vector at the receiver and target, respectively.

The power reflected from the j^{th} scatterer and incident upon a receiving antenna with an effective area, A_e , is

$$P_{rj} = \frac{G_t^2 f_t^2(\theta, \phi) f_r^2(\theta, \phi) e^{-4\alpha R_j} P_t A_e \sigma_j}{(4\pi)^2 R_j^4}$$

By assuming that the transmitter and receiver antenna are identical and using the definition of receiver antenna gain

$$G_r = \frac{4\pi A_e}{\lambda^2},$$

the expression for received power is

$$P_{rj} = \frac{G^2 \lambda^2 f^4(\theta, \phi) e^{-4\alpha R_j} P_t \sigma_j}{(4\pi)^3 R_j^4}$$

which follows directly from the preceding definitions. The assumption of independent scatterers (and this is the crucial assumption of the analysis), allows the total received power from the fracture surface to be considered as the sum of all of the individual returns,

$$P_r = \frac{G^2 \lambda^2}{(4\pi)^3} \sum_{j=1}^n \frac{f^4(\theta, \phi) e^{-4\alpha R_j} P_t \sigma_j}{R_j^4}$$

Assuming a large number of scatterers uniformly distributed with a density, $N(\sigma)$, and using the (z, θ, ϕ) coordinates of Figure 2.4 with the fracture plane making an angle, ζ , with respect to the borehole, the summation is replaced by the integral

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^2 z^2} \int_{-\pi}^{+\pi} \int_0^{\pi/2} \int_0^{\infty} f^4(\theta, \phi) e^{-4\alpha z / \sin(\theta + \zeta)} \sigma N \sin(\theta + \zeta) d\theta d\phi d\sigma,$$

where we have considered only the special case for which the radar beam lies in the plane containing the borehole and the normal to the fracture surface from the position of the radar set. The integral over σ is a dimensionless cross section whose value cannot be determined by this simple theory. Although not exact, we shall identify the dimensionless cross section with the plane wave reflection coefficient, r , which is defined as the ratio of the normal components of the reflected Poynting vector to the incident Poynting vector. On physical grounds, it is clear that because of the reduction in signal strength arising from dissipation the upper limit on the integral over ϕ need only extend to some finite (but as yet unspecified) value. The integral over ϕ defines a beam width, Φ . For a very narrow beam in the θ direction, the function, $f^4(\theta)$, varies much more rapidly than the other quantities in the integrand and they may therefore be taken outside the integral. The remaining integral over $f^4(\theta)$ defines a beam width, Θ . This result holds only for a narrow beam. If $f^4(\theta, \phi)$ varies over a large region of space, then the particular antenna pattern function must be integrated along with the other terms in the integrand. Thus, the received power from a narrow beam reflected from a large plane surface is

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 z^2} \Theta \Phi r e^{-4\alpha R} \sin(\theta + \zeta) . \quad (2.7)$$

At near normal incidence, the result is

$$P_r = \frac{P_t G^2 \lambda^2 \Theta \Phi r e^{-4\alpha R}}{(4\pi)^3 R^2} . \quad (2.8)$$

In addition to the attenuation caused by the complex permittivity, the received signal is further reduced by the square of the distance between the radar set and the reflecting surface. The reduction in range caused by $1/R^2$ -spreading can be seen in Figure 2.3 by comparing this result with that of the perfectly collimated beam. In evaluating Equation 2.8, we have assumed that $\Theta = \Phi = 1$ radian, and that $G = 4\pi/(\Theta\Phi)$. Over the

frequency band considered $10^7 \leq f \leq 10^{10}$ Hz, $1/R^2$ spreading results in a reduction of range that is less than 25 percent of that of a perfectly collimated beam. The $1/R^2$ dependence for near-normal incidence on the surface of the sea has been confirmed by experiments with airborne radar; we expect the same relationship to hold in a subterranean setting if a narrow beam antenna can be devised to fit within a sonde.

2.4 THE RANGE OF A WIDE BEAM RADAR ILLUMINATING A LARGE PLANAR FRACTURE

We now turn to estimating the maximum range of a radar with a relatively wide beam such that (i) only a fraction of the radiated power falls on the fracture plane, and (ii) the antenna pattern function is essentially constant, i.e., the antenna is very nearly an isotropic radiator. We do so for several reasons. At the present time, a narrow beam borehole radar for $f \leq 10^9$ Hz does not exist. For $f > 10^9$ Hz, where the wavelength is comparable to or less than the borehole diameter, it should be entirely possible to build a directional antenna, but because of the relatively short range of radar operating at $f \geq 10^9$ Hz and because of a new fracture identification technique reported in Section 3 which must operate with $f \leq 3 \times 10^8$ Hz, we concentrate on VHF radar. By considering a fracture plane to have an effective radar backscatter cross section, σ , and setting $f(\theta, \phi) = 1$, the expression for the received power is

$$P_r = \frac{P_t G^2 \lambda^2 e^{-4\alpha R} \sigma}{(4\pi)^3 R^4} \quad (2.9)$$

The problem is now one of determining σ . In calculating reflections from the earth's surface, an analysis of wave interference effects leads to the result that the main contribution to the reflection arises from the first Fresnel zone [20]. Recall that Fresnel zones in a lossless medium are constructed in such a way, either on a wave front or on a reflecting surface, that the amplitude of excitation associated with each zone varies slowly from zone to zone, but that a phase reversal occurs between adjacent zones so that at an observation point the contributions of successive zones essentially cancel each other except for the radiation from half the area

of the first zone and from the entire last zone. The cancellation comes about, of course, because the path lengths to adjacent zones differ by $\lambda/2$. It is usually supposed that a lack of longitudinal coherence causes the contribution from the last zone to vanish, leaving only the contribution from one-half of the first zone [21]. Thus, $\sigma \approx \frac{1}{2}\lambda(R+\lambda) \approx \frac{1}{2}\lambda R$. In estimating the range of subterranean radar, Cook [3] effectively arrived at the same results for the cross section. The Fresnel zone argument strictly applies only to normal incidence and to a lossless medium. At oblique incidence, the zones are elliptical, and cancellation is not assured between adjacent zones. In a lossy medium, the amplitude varies between adjacent zones and exact cancellation will not occur, but only a relatively small number of zones need be considered in the determination of the cross section because of the reduction in amplitude as the zone number increases. For the purpose of making a rough estimate, we shall use the Fresnel zone model, but to account for imperfect reflection, we reduce the backscatter cross section by a reflection coefficient. Equation 2.9 then becomes

$$P_r = \frac{P_t G^2 \lambda^3 e^{-4\alpha R}}{128\pi^3 R^3} \quad (2.10)$$

The received signal is reduced by the cube of the range between the radar set and the reflecting surface, over and above that caused by dielectric losses. The reduction in range caused by the $1/R^3$ behavior can be seen in Figure 2.3 by comparing this result with that of a perfectly collimated beam and with a narrow beam. In evaluating Equation 2.10, it was assumed that the antenna was a half-wave dipole with $G = 1.64$. Over the frequency band considered, $10^7 \leq f \leq 10^{10}$ Hz, the use of a half-wave dipole reduces the range by less than 25 percent of that of a highly directive antenna. The main problem with the dipole is not the reduction in range, but rather the inability to resolve the angular position of a fracture.

2.5 THE EFFECTS OF THE REFLECTION COEFFICIENT, RESERVOIR TEMPERATURE AND FRACTURE ROUGHNESS ON RADAR PERFORMANCE

The calculations of Sections 2.2-2.4 are useful for estimating the maximum range of a subterranean radar and for comparing the relative effects of dielectric losses, beam spreading and transmitter power. The calculations were made with $r = 1$ and $T = 280^{\circ}\text{C}$ (550°K). Since the reflection coefficient will, in general, be less than one, and the temperature can be either greater or smaller than 280°C , it is important to estimate the variation in range with r and T . Moreover, in one of the calculations, it was assumed that the reflection was specular, while in the other two, it was assumed that the reflection was diffuse. We now quantify the effects of the reflection coefficient, the reservoir temperature and the nature of the reflecting surface.

2.5.1 The Variation of Range with Reflection Coefficient

In the formulas for the range, the transmitter power and the reflection coefficient always appear as a product so that the reduction in range caused by the reflection coefficient having a value less than 1 can be estimated immediately from Figure 2.3 if the plots for $P_t = 10$ watts, $r = 1$ are used to represent $P_t = 10^4$ watts, $r = 10^{-3}$. For the $1/R^2$ law, a 0.1% reflection coefficient reduces the range to between 70% to 80% of its value with $R = 1$, while for the $1/R^3$ -law, the reduction is between 65% to 75%. The actual value of r that occurs at a fracture depends upon the geometry of the fracture, the loss tangent, differences in ϵ and σ between the fracture material and the surrounding rock, the polarization and the angle of incidence. In general, a boundary value problem in which all of these variables are accounted for must be solved to obtain r . On physical grounds, if the fracture has a large lateral extent compared to the beam width or if the loss tangent causes a large decay in the signal strength across the lateral face of a fracture, then Fresnel's formula /9/ for plane wave reflection coefficients should provide a good approximation to r . In this section we assume that the fractures of interest fulfill one or both of these conditions, and accordingly,

we employ Fresnel's results. To further simplify the problem, only the case of normal incidence is considered. For the time being, we restrict our attention to water inflated cracks, deferring a discussion of naturally occurring fractures to Section 3. The fracture model is particularly simple; namely, a single planar crack with thickness, d , exists within a mass of rock whose boundaries are far away from the crack. Because water has a much greater conductivity than rock, Fresnel's formulas are implemented by assuming that the host rock is lossless, while the fracture is characterized by a finite loss tangent. Under these conditions, the reflection coefficient is expressed by the relation

$$r = \frac{r_{12} \left[\left(1 - e^{-2\alpha_2 d} \right)^2 + 4e^{-2\alpha_2 d} \sin^2 \beta_2 d \right]}{\left(1 - r_{12} e^{-2\alpha_2 d} \right)^2 + 4r_{12} e^{-2\alpha_2 d} \sin^2 (\delta_{12} + \beta_2 d)}, \quad (2.11)$$

where for a nonmagnetic material

$$r_{12} = \frac{(\beta_1 - \beta_2)^2 + \alpha_2^2}{(\beta_1 + \beta_2)^2 + \alpha_2^2}$$

$$\delta_{12} = \tan^{-1} \left[\frac{2\beta_1 \alpha_2}{(\beta_2^2 + \alpha_2^2) - \beta_1^2} \right],$$

d is the crack thickness, α and β are defined in Subsection 2.1, and the subscripts 1 and 2 refer to rock and water, respectively.

The reflection coefficient, evaluated from Equation 2.11, is plotted in Figures 2.5 through 2.7 as a function of crack thickness with the frequency, water purity and to a limited extent the temperature as parameters. Within the framework of a single crack model (and the validity of the model itself remains to be established), an inflated fracture might have a thickness of 1 to 2 mm. The plots extend to 10 mm, not because it is believed that a crack could have such a great thickness,

Figure 2.5. Plane wave reflection coefficient for normal incidence on a planar fracture filled with distilled water at 25°C as a function of crack thickness and frequency.

Figure 2.6. Plane wave reflection coefficient for normal incidence on a planar fracture filled either with fresh water, or Fenton Hill water recycled for ten days, or 0.5 molal NaCl as a function of crack thickness and frequency.

Figure 2.7. Plane wave reflection coefficient at high frequencies for normal incidence on a planar fracture filled with 0.5 molal NaCl at 25°C as a function of crack thickness.

but rather to illustrate trends. The frequency range, $10^7 \leq f \leq 10^{10}$ Hz, illustrates the need for a high frequency to obtain a large reflection coefficient from very narrow cracks with $d < 1$ mm. The water purity considered ranges from that of distilled water to highly saline water and includes effluent from the Fenton Hill Hot Dry Rock System. Calculations based upon the properties of distilled water are unrealistic for a geothermal fracture system because the ions present in the circulating fluid will markedly increase the electrical conductivity over that of pure water. Nevertheless, the data for distilled water are quite well known and provide an accurate lower bound on the reflective power of water filled cracks. At the other end of the purity scale, a 0.5 molal NaCl solution (2.24×10^4 ppm), which also has accurately measured properties, provides a good upper bound on the reflective power. In between these two limits lie the results for Fenton Hill effluent. Lack of data has restricted calculations of temperature effects to 25°C and 85°C for distilled water only. Data for liquid water at $200 \leq T \leq 400^\circ\text{C}$ are needed, but are apparently unavailable.

Calculations based upon the properties of distilled water at 25°C , Figure 2.5, indicate that the frequency should be 10^8 Hz or greater to have $r \geq 10^{-3}$. At $f = 10^{10}$ Hz, the reflection coefficient is large even for $d = 0.2$ mm, but the range in granite at this frequency is less than 1 meter. The reflection coefficient is a damped oscillatory function of the crack thickness as evidenced by the curve for $f = 10^{10}$ Hz. The three lower frequency curves are still in the resonance region for $d < 10$ mm and have not yet decayed to their asymptotic value of $r = 0.3$.

The increased conductivity of water that had been recycled for ten days /22/ causes the reflection coefficient at $f = 10^7$ Hz to be three times that of fresh water newly added to the Fenton Hill heat transfer loop, Figure 2.6. At 10^8 Hz, recycled water and fresh water yield identical values of r . A significant result which appears to have very important practical implications is that for 0.5 molal NaCl, the reflection coefficient is quite high and is essentially invariant with frequency for

$10^7 \leq f \leq 3 \times 10^8$ Hz. The rather remarkable behavior of the reflection coefficient for saline solutions prompted us to extend the calculations to higher frequencies, Figure 2.7. At $f \geq 10^9$ Hz, the reflection coefficients for saline water and distilled water are not much different, implying that the role of ionic conduction is no longer crucial. This result is discussed at greater length in Section 3. Upon comparing Figures 2.5 and 2.6, it is noted that the reflection coefficient at 10^8 Hz for distilled water is calculated to be greater than that for either fresh or recycled water. This inversion of physical reality almost assuredly stems from assuming in the calculation of the loss tangent of Fenton Hill effluent that the conductivity is a constant rather than an increasing function of frequency. (Neither the frequency nor the temperature at which the measurements were made were reported in Reference 22.)

An increase in temperature from 25°C to 85°C reduces the reflection coefficient by a greater amount at low frequencies than at high frequencies, e.g., a factor of two at 10^8 Hz, but only fifteen percent at 10^{10} Hz, Figure 2.8. It is important to recognize that test measurements made at room temperature may yield overly optimistic range predictions. For completeness, the electrical properties of water under various conditions of purity and temperature are listed in Table 2.1.

The reduction in maximum range caused by reflection coefficients that might be experienced in practice can now be calculated using the preceding results. Choosing a fracture thickness of 2 mm, the farthest range for the detection of a fracture filled with (i) a 0.5-molal NaCl solution, and (ii) Fenton Hill effluent recycled for ten days is plotted and compared with that of a perfect reflector in Figures 2.9 and 2.10 for narrow beam and wide beam antennas, respectively. The reduction in range is not significant.

2.5.2 The Variation of Range with Reservoir Temperature

The reservoir temperature affects the maximum range by setting the level of thermal noise generation and by altering the dielectric properties of the rock itself and of the water within the fractures. By noting that

Figure 2.8. Plane wave reflection coefficient at slightly elevated temperature for normal incidence on a planar fracture filled with distilled water at 85°C as a function of crack thickness and frequency.

Table 2.1. Electrical Properties of Water

	f (Hz)	κ_e	$\tan \delta$
Distilled @ 25°C	10^7	78.2	4.6-03
	10^8	78.0	5.0-03
	10^9	76.9	5.3-02
	10^{10}	55.0	5.4-01
Distilled @ 85°C	10^7	58.0	1.3-02
	10^8	58.0	3.0-03
	10^9	56.8	2.1-02
	10^{10}	54.0	2.6-01
0.5 Molal NaCl @ 25°C	10^7	72.9	1.1+02
	10^8	70.3	1.1+01
	10^9	68.0	1.5
	10^{10}	51.0	6.3-01
Fresh Effluent Fenton Hill	10^7	72.9	3.5-01
	10^8	70.3	3.6-02
	3×10^8	69.0	1.2-02
Recycled 10 Days Fenton Hill	10^7	72.9	1.5
	10^8	70.3	1.5-01
	3×10^8	69.0	5.2-02

Figure 2.9. Reduction in maximum range based on $1/R^2$ -law caused by imperfect reflection at a 2 mm thick planar fracture.

Figure 2.10. Reduction in maximum range based on $1/R^3$ -law caused by imperfect reflection at a 2 mm thick planar fracture.

the reduction in received signal strength caused by imperfect reflection can be accounted for in Equation 2.6 by multiplying P_t by r , it is seen that the effect of temperature is not a strong one insofar as the reflection coefficient and the thermal noise are concerned: The range varies only logarithmically with these quantities. However, any variation of the attenuation coefficient with temperature has a direct effect on the range. Data apparently are not available to allow $r(T)$ and $A(T)$ to be estimated. The reduction in range caused by an increase in thermal noise at elevated temperatures is entirely negligible over the interval $25 < T < 400^\circ\text{C}$, $10^7 \leq f \leq 10^9$ Hz, amounting to less than 5 percent for both the $1/R^2$ and $1/R^3$ laws.

2.5.3 The Effect of Fracture Roughness on Radar Scattering

The angular dependence of an electromagnetic wave reflected from a fracture surface depends upon the roughness of the surface compared to a wavelength. The term roughness is used to describe the height of irregularities, their lateral extent and spatial distribution. Irregularities can be thought of as arising from two sources, either grain breakage or block fault motion. The former produce asperities that are less than about five millimeters in size for a coarse grained granite and are not important within the frequency range that we have considered. The latter are important and their characteristics have been estimated using (i) logs from Fenton Hill to obtain the block spacing, and (ii) general field experience to set the relative slip along a fracture as a function of fracture tightness, as discussed at some length in Section 7. Pertinent results from that section are summarized in Table 2.2, in which five types of weakness planes, identified from Fenton Hill borehole logs in terms of the strength of their signatures, are characterized by a differential slip and an average fracture spacing in a random direction. It is assumed that a producing fracture will be one of the more prominent fractures, i.e., type 1. Thus, the roughness on the surface of the type 1 fracture will be caused by offsets arising from slip along the other weakness planes which intersect the type 1 fracture. The distance between these intersections on the type 1 fracture varies between 2 and 55 meters, Table 2.2.

The effective roughness height is reduced from the slip offset by the sine of the intersection angle (see Figure 7.1) which is inferred to be approximately 0.75 for vertical wellbores in the Fenton Hill geology. In summary, the height of the irregularities is caused by fault slippage, while the lateral extent and the spatial distribution of the irregularities are the inverse of one another and are set by the block size.

Table 2.2. Fracture Plane Offsets and Spacings

Weakness Type	Differential Slip (m)	Average Spacing Between Fractures (m)	Spacing on Main Fracture (m)
1	10^{-1} - 1.0	40	55
2	10^{-2} - 10^{-1}	10 - 13	20
3	10^{-2} - 10^{-1}	10 - 40	40
4	10^{-3} - 10^{-2}	4 - 7	8
5	0 - 10^{-3}	1.3	2

If an electromagnetic wave can maintain phase coherence as it traverses a fracture system, then a reflection will tend to be specular; if not, the reflection will tend to be diffuse. If we assume for the moment that irregularities are uniformly distributed over the reflecting surface, then the Rayleigh criterion /21/ can be used to determine if the reflection will be specular or diffuse. Rayleigh's criterion is formulated in the following way. Let h be the height of an irregularity and ψ the grazing angle (the complement of the angle of incidence). Then the path difference between the ray that strikes the top of an irregularity and the ray that strikes its base is $\Delta R = 2h \sin \psi$, and the phase difference is

$$k\Delta R = \frac{4\pi h}{\lambda} \sin \psi .$$

If the phase difference is small, the surface is effectively smooth. As the phase difference approaches π , the two rays interfere destructively. Although there is no well established practice in the matter, the crossover between specular and diffuse reflection has been placed at a phase difference of $\pi/2$, which gives the criterion

$$h \sin \psi < \lambda/8$$

for the reflection to be considered specular. In view of the uncertainty attendant to establishing h in a geothermal reservoir, the crude Rayleigh theory is sufficient for our purposes. We further simplify the problem by considering only normal incidence ($\psi = \pi/2$) and plot in Figure 2.11 the boundary between specular and diffuse reflection in terms of the size of surface irregularities and the radar frequency. With a maximum roughness height of 7.5 cm (obtained under the previously described conditions), specular reflection will occur for $f < 2 \times 10^8$ Hz. The average roughness may well be less than 7.5 cm in which case the crossover between specular and diffuse reflection will move to a higher frequency. For frequencies greater than the crossover frequency, reflections will be truly diffuse only if there are a large number of irregularities within the illuminated region. If the primary reflecting region is taken to be the first Fresnel zone, then the number of irregularities within the zone must be large for the reflection to be diffuse. The diameter of the first Fresnel zone as a function of frequency is plotted in Figure 2.12. Only the region $f > 2 \times 10^8$ Hz needs to be investigated for at lower frequencies the reflection is always specular. Based on the model used to calculate Table 2.2, it is clear that for $2 \times 10^8 < f \leq 10^9$ Hz there is at most one offset within the main reflecting zone. The reflection will assuredly not be diffuse, but rather will exhibit a scattering pattern caused by a step offset. Implicit in this deduction is the assumption that the cancellation of the reflections from the higher order Fresnel zones will not be markedly altered by a step which cuts across the zones. A detailed calculation of the reflection from a stepped surface appears to be necessary for interpreting scattering from a fracture plane.

Figure 2.11. Boundary Between Specular and Diffuse Reflection for Normal Incidence as a Function of Surface Roughness and Frequency, Based on Rayleigh's Criterion.

Figure 2.12. Diameter of First Fresnel Zone at Maximum Range vs. Frequency.

SECTION 3

FRACTURE DETECTION

Rather than being a monolithic block of granite, a hot dry rock reservoir is likely to be crisscrossed by a large number of fractures and dikes. This is the picture that has been pieced together from conventional logging measurements made at the Fenton Hill site (Section 7). Thus, the task of a radar mapping tool is not only to detect fractures that can provide potentially useful heat transfer surfaces, but also to distinguish between a fracture and an electrical anomaly associated with a dike or other intrusive material. The latter task is complicated because a narrow water-filled fracture and a mineral intrusion can have the same value of the reflection coefficient (at least up to some limiting value set by the properties of the intrusion and the host rock). Because the dielectric properties of an intrusive material like quartzite are more nearly like those of granite than are those of water, it is clear that for equal values of the reflection coefficient a dike must be much thicker than a water-filled fracture. For example, upon comparing Figures 2.5, 2.7, 2.8 and 3.1, it can be seen that the minimum thickness of a quartzite intrusion ($\kappa_e = 4$) in granite ($\kappa_e = 6$) that produces a one percent reflection coefficient for normal incidence at $f = 10^9$ Hz must be thirty times greater than that of a water-filled fracture, i.e., the thickness of a water-filled fracture is approximately 0.4 mm, but the thickness of a quartzite intrusion must be at least 12.5 mm. The reflection coefficient at the granite-quartzite interface is an oscillatory function of the intrusion thickness which has a maximum value of 0.04 at a thickness of 40 mm and then gradually approaches $r = 0.01$ as the intrusion becomes very thick. Thus, if backscatter signals are compared solely on the basis of amplitudes, it is not possible to differentiate between a thick quartzite intrusion and a thin water-filled fracture with a thickness less than approximately 0.7 mm. However, cracks and intrusions which produce identical reflection coefficients will, in general, have

Figure 3.1. Minimum Intrusion Thickness for a One Percent Radar Reflection Coefficient. Ratio of Intrusion κ_e to Host $\kappa_e = 2/3$.

different wave transit times across the feature. In the previous example, the crack and intrusion thickness differ by a factor of 31.3, while wave speeds differ by a factor of 4.1 to yield a transit time difference of 7.6. In principle, it should be possible to differentiate between a fracture and an intrusion on the basis of their backscattered waveforms. At the present time, the analyses necessary to implement such a procedure have apparently not been performed. Moreover, it is far from certain that water naturally exists between the faces of a fracture in a hot dry rock reservoir. It is quite possible that the largest backscatter signals would arise from relatively wide intrusions and that tight dry fractures would be relatively transparent to radar.

The uncertainty that currently exists in distinguishing between fractures and electrical anomalies can be eliminated, and positive identification can be assured by the use of a rather simple technique for that class of fracture which intersect the borehole. By inflating a fracture with an electrically conducting material, say 0.5 molal or greater saline water and by using a frequency of approximately 3×10^8 Hz, the reflection coefficient at the fracture is greatly increased over what it would be under normal conditions. Three radar scans are possible: (i) uninflated to yield a background measurement, (ii) inflated with either fresh or recycled water to provide a return signal from wide fractures, and (iii) inflated with saline water to provide an 8- to 10-db increase in signal strength over (ii). The main idea is to produce an enhanced signal from a fracture that will stand out from the backscatter produced either by electrical anomalies or by numerous, but minor, fractures. For $f \leq 3 \times 10^8$ Hz, the reflection coefficient for normal incidence is greatly increased when saline water is injected into a planar fracture as is readily seen by comparing Figures 2.5 through 2.8. Thus, permeable planar fractures can be made to stand out from background noise by injecting an electrically conducting fluid into the fracture and by using a suitable frequency. At very high frequencies, the contrast disappears as the lossiness switches from ionic conduction to molecular

excitation, which restricts the frequency band to less than approximately 3×10^8 Hz. Not only do the lower frequencies at $f \leq 3 \times 10^8$ Hz provide the necessary contrast, but they also provide a longer range than can be attained at higher frequencies. To take full advantage of this technique requires the development of a directional borehole antenna for $f \leq 3 \times 10^8$ Hz.

SECTION 4

RADAR SUMMARY

According to calculations, VHF radar has the potential for mapping fractures within a region of a hot dry rock reservoir that extends away from the wellbore for a distance of approximately 50 ± 20 meters. This range is sufficiently great to make radar a useful tool if two other requirements can be satisfied. To realize the full potential of backscatter radar as a mapping tool, a directional and steerable VHF antenna must be developed to provide both azimuthal resolution and the ability to detect fractures that are nearly normal to the borehole. In the VHF band, the development of a highly directional and steerable borehole antenna is a very difficult problem. (At higher frequencies, in the UHF band, directionality can be readily obtained from an antenna that can fit within a wellbore, but other issues regarding range and antenna coupling have yet to be settled.) As the angle between a borehole and a fracture becomes larger and approaches $\pi/2$, the backscatter signal becomes weaker. Thus, the geometry of the second phase Fenton Hill system which employs boreholes intersected by nearly perpendicular fracture planes is less well-suited to radar backscatter experiments than is the geometry of the first phase system where the borehole and fractures were more nearly parallel. The use of radar transmission experiments for the case of a wellbore that is nearly perpendicular to a fracture plane will be studied during the next phase of the contract. It is noted, however, that a wellbore-to-wellbore separation distance in excess of 100 meters may preclude the use of radar transmission experiments.

The second unfulfilled requirement levied on a radar system is target identification, which is in a rudimentary state. Experiments have shown that the clear-cut identification of subterranean targets is a formidable task. Based on an analysis of fracture reflectivity, it is believed that fracture identification can be greatly enhanced by inflating a fracture with a conductive fluid, e.g., salt water. A comparison of radar echoes in the pressurized and non-pressurized states should make a fracture appear quite prominent.

SECTION 5

CHARACTERIZATION OF BOREHOLE FRACTURE INTERCEPTS USING CONVENTIONAL BOREHOLE LOGGING SURVEYS

Conventional borehole logging techniques are an important and necessary part of a fracture mapping program. As shown in this and the subsequent section, conventional techniques can be employed to (1) determine the number and size of fractures and weakness planes intersecting a borehole, (2) define the fracture orientation at the borehole, (3) develop an approximate model of the natural fracture pattern around the borehole, (4) suggest regions for inducing hydraulic fractures, (5) determine the location and width of hydraulic fractures, and (6) locate connection points between wellbores. Aside from temperature limitations which restrict the use of all borehole tools, the most serious shortcomings of conventional techniques are (1) an inability to determine the far-field extent and orientation of hydraulically induced fractures, and (2) the failure of any one tool to provide an accurate and unambiguous determination of fracture location and orientation.

Before proceeding, it is appropriate to note that the term conventional borehole techniques is used to mean those methods normally employed by logging companies and drilling contractors to service the petroleum industry. In almost all cases, wireline techniques would be more useful for geothermal logging if the equipment could handle higher temperatures. In some cases, data reduction would be improved if analyses were developed specifically for unfolding data obtained in fractured hard rock rather than relying on methods developed for use in sedimentary strata. Certain techniques which are commonly used for logging in sedimentary rock have been found to be of marginal value in a hot dry rock reservoir. However, even without improved analyses, fracture locations can often be inferred by crosscorrelating records from a suite of appropriate tools as indicated in Subsection 5.2.

For the purpose of fielding an effective fracture mapping program, it is useful to divide the construction of a hot dry rock reservoir into four operations: (1) drilling, (2) pre-hydraulic fracture, (3) post-hydraulic fracture, and (4) two-well completion. The type of data that can be obtained during

drilling is usually related to the lithology and is rather general in nature, except for those gathered from an occasional traverse by a sonde during a break in drilling operations. (Logging-while-drilling via a telemetry link would improve the situation, but it is not yet a practical reality.) The types of logs that can be obtained during a drilling operation and their usefulness are discussed in Subsection 5.1. Knowledge of the natural structure of a reservoir, i.e., the pattern of fractures and dikes, is valuable for planning hydraulic fractures, interpreting test data, and inferring the existence of leakage paths. A number of techniques employing mechanical, electrical, optical, and radiochemical methods can map borehole fracture intercepts when used synergistically during the pre-hydraulic fracture phase as discussed in Subsection 5.2. Mapping after hydraulic fractures have been created is crucial both for setting the direction of subsequent drilling and for determining the position of likely flow connections. Techniques used during this phase are similar to those of the pre-hydraulic fracture phase except that fluid flow measurements become more viable, as discussed in Subsections 5.3 and 5.4. The final operation is one of measuring the position and size of flow connections between wells. Tracer methods, reviewed in Subsection 5.4, along with temperature and flow measurements complete the discussion of conventional techniques.

For convenience of reference, all of the techniques discussed in this section are listed in Table 5.1 along with the operation during which they would be utilized.

5.1 LOGGING DURING DRILLING OPERATIONS

Logs recorded during drilling operations provide the initial characterization of subsurface fracturing. The logs are obtained from the assay of material removed from or circulated through the wellbore, the monitoring of drill performance, and an occasional sonde traverse when the drill bit has been removed for servicing. The logs are normally run to assist drilling; from the standpoint of fracture mapping, they are rather coarse. Nonetheless, if the logs are carefully taken, they provide the first indication of either fracture or injection zones, and may help to resolve anomalies that appear during fracture mapping operations.

Table 5.1. Techniques for mapping borehole fracture intercepts and their application during the four main operations associated with constructing a hot dry rock geothermal reservoir.

Log	Operation			
	Drilling	Pre-Hydraulic Fracture	Post-Hydraulic Fracture	Two-Well Completion
Drill Cutting	X			
Drill Rate	X			
Fluid & Mud	X			
Core	X			
Caliper	X	X	X	
Resistivity		X	X	
Televiewer		X	X	
Television		X	X	X
Impression Packer		X	X	
Acoustic Transmission		X	X	
Density		X	X	
Spontaneous Potential			X	
Gamma Ray		X		
Spectralog		X		
Silicon/Calcium		X		
Temperature	X			
Temperature (Differential)		X	X	X
Spinner			X	X
Tracer			X	X

5.1.1 Drill Cutting Log

Circulating drill fluid carries rock chips or drill cuttings from the bit to a surface settling pond where samples are either taken at intervals or extracted continuously. Petrological analyses of the chips are used to differentiate between rock units. Since the chips are small, color changes tend to be the dominant first indicator of rock unit boundaries. The identification of minerals that are known to deposit in fractures is a potential indicator of fracture zones. Because of mixing and the inaccuracies in determining the transit time of a chip from the bit to the surface, the order in which chips were excavated and the depth at which a chip originated cannot be known exactly. Therefore, the depth of a rock unit or an inferred fracture zone is usually uncertain to within 2 to 10 feet, depending on the drilling rate, sampling frequency, circulation pump rate, and the care exerted by the logging crew. An example of a chip log delineating rock type as a function of depth at the Fenton Hill reservoir is shown in Figure 5.1, along with three other types of logs. Rock types and rock boundaries based upon the chip log as reported by West /23/ are indicated between a depth of 2500 feet to 4300 feet. Without going into the details of the other logs (see Subsection 5.2), it is noted that the chip log correctly identified two major zones containing dikes (weakness planes), but was not useful for predicting the locations of the fractures.

To refine and clarify interpretations based on the drill cutting log, and to provide almost incontrovertible evidence of subsurface properties, core samples are taken occasionally. Direct fracture characterization would be possible if the borehole were completely core drilled with an orientation scribe and the core 100 percent recovered. Expense prohibits such drilling, and 100 percent core recovery is virtually impossible.

5.1.2 Drill Rate Log

The rate of descent of a drill into the ground is commonly recorded automatically. By monitoring pull-down pressure and torque, the drill rate log can be a sensitive indicator of changes in rock resistance to drilling when combined with data on bit wear rates under similar drilling conditions. Changes in apparent hardness can be compared with logs taken later on during

Figure 5.1. Fracture distribution inferred from crosscorrelation of four different conventional borehole logs. Data from upper portion of hole GT-2 at Fenton Hill obtained from chip analyses, silicon log, background gamma ray, and two-independent-arm caliper measurements. Nomenclature: Gr (granite), Grd (granodiorite), Mgr (Monzogranite), Sgr (Syenogranite), FZ (zone of multiple fractures), CA (zone of chemical alteration usually characterized by borehole erosion), ? (interpretation uncertain). To aid crosscorrelation of contact alterations with eroded zones, the silicon log is modified with the following visual aid: Si < 6, Si ~ 6, Si ~ 7, and Si > 7.

the pre-hydraulic fracture phase to assist in locating chemically altered or fractured zones.

5.1.3 Fluid and Mud Logs

A detailed record of the analyses of drilling-fluid samples, and notations of even small fluid losses are important to fracture mapping and weakness characterization. Analyses of fluid samples can determine changes in the chemistry of the fluid arising from interactions with the rock. Zones of lost fluid indicate penetration into the surrounding rock, an early signal of open, permeable fracture zones. These logs appear to lose their effectiveness at depths in excess of about 8000 feet because the lithostatic pressure decreases the permeability of natural fractures.

5.1.4 Initial Sonde Traverse

The first sonde that is run into an unstudied hole is usually rather simple, consisting in most cases of no more than two tools: an inexpensive two-independent-arm caliper and a maximum temperature recording thermometer. The caliper is used primarily to measure borehole geometry and to detect obstructions that could cause a sonde to become lodged in the drill hole. (At worst, if the first sonde gets stuck in the drill hole, it is milled out, and the economic loss is kept to a minimum.) A maximum temperature recording thermometer is used to give a rough indication of formation temperature and is attractive from an operational standpoint because of its simplicity, although rough handling may result in shock-induced errors. A continuous temperature measurement is of considerably more value for fracture mapping than a peak record because of its ability to detect temperature anomalies which may occur at permeable, fractured zones. This usefulness for fracture detection is undiminished by the fact that during drilling the borehole is not in temperature equilibrium with the surrounding reservoir, i.e., for the purpose of thermal engineering, a continuous temperature record during drilling is not especially useful in a hot dry rock reservoir. (The continuous record is quite important in a hydrothermal reservoir.) The caliper and temperature logs that are obtained during the drilling operation are useful for providing a first rough picture of fracture intercepts at the borehole. They

are, however, capable of considerably better precision than is usually attained during the first logging runs, as discussed in Subsections 5.2 and 5.4.1, respectively.

5.2 LOGGING DURING PRE-HYDRAULIC FRACTURE OPERATIONS

Fourteen different techniques were evaluated for their effectiveness in mapping the intersections of natural fractures with a borehole. The techniques are listed in Table 5.2. Variation of the basic methods increase the number of techniques available to more than thirty. Based mainly on experimental performance, six techniques appear quite useful: (1) caliper, (2) resistivity dipmeter, (3) televiwer (acoustic imaging), (4) television, (5) impression packer, and (6) acoustic transmission. The dipmeter and acoustic transmission methods require improved analyses, while all six could benefit from improved high temperature capabilities. A seventh technique, the silicon/calcium log, is useful for differentiating between fractures and zones of chemical alteration, but is in itself not capable of detecting fractures. Six other techniques appear to be of marginal value for locating fractures at the present state-of-the-art. They are the (1) density log, (2) spontaneous potential, (3) resistivity methods that sample large volumes of rock, (4) gamma log, (5) spectralog, and (6) temperature log. A differential temperature measurement might conceivably record temperature changes arising from fluid seepage at natural fractures, but the technique has not been tested in a hot dry rock reservoir. The temperature logs appear useful for mapping hydraulic fractures under forced flow conditions; discussion of these logs is deferred to Subsection 5.4. Because of its impact on cost and the compatibility of different tools on a single sonde, the logging rate for each tool is listed in Table 5.2. A persistent problem in crosscorrelating logs to locate fractures in a deep, hot geothermal well is an apparent depth offset of several feet between logs; a remedy to the problem is suggested in Subsection 5.2.9.

5.2.1 Caliper Logs

After the drill bit, the rotating drill pipe, and the drilling fluid have produced wear on the borehole wall, caliper logs provide a sensitive

Table 5.2. The use and limitations of logging techniques for the detection of natural fracture intercepts at a wellbore reviewed in Subsection 5.2. The logging rate gives a rough indication of cost and compatibility of different tools on the same sonde.

Technique	Usefulness and Limitations	Logging Rate, fps
Caliper	Three independent arms required	70
Spontaneous Potential	No direct relation between SP and fractures.	100
Resistivity Diplog	Detects fluid-filled fractures. Standard data reduction codes suspect. Additional work warranted.	50
Normal Electric	Diffuse record. Cannot locate isolated fractures.	100
Induction	Fair correlation with caliper. Additional work required, but dipmeter appears superior.	100
Televiewer	Useful acoustic image of fracture intercepts and borehole surface.	6
Television	Useful optical image of fracture intercepts, fluid flow, and borehole surface. Not used in hot dry rock program. Requires thermal hardening. Photography may be more expedient.	
Impression Packer	Three-dimensional record of fracture size and orientation. Unreliable operation even at modest temperatures (150°C).	
Acoustic Logs	Cycle skipping: Irregular and often unreproducible effect. Uncertain results. Amplitude reduction: Useful for correlation. No clear-cut advantage over waveform recording. Interpretation uncertain. Waveform analysis: Contains all acoustic information but interpretation uncertain. Phase Splitting: Interpretation uncertain. Requires additional work.	60

Table 5.2. Continued

Technique	Usefulness and Limitations	Logging Rate, fps
Radiochemical	Silicon/calcium: Distinguishes chemically altered zones from fracture.	25
	Gamma Ray: Poor correlation with caliper log.	30
	Spectralog: As with Si/Ca and γ -ray logs, no close correlation with fractures.	11
Formation Density	Spurious responses. Requires calibration tests in hard rock of known fracture porosity.	30
Temperature	Used for locating fractures under forced fluid flow conditions. Differential temperature not tested.	65

measure of the resistance of the rock to erosion. Commonly, the caliper logs correlate well with the drill rate logs, since they both reflect hardness, degree of fracturing, and easily eroded zones that in igneous rock may be zones of chemical alteration. By itself, a caliper cannot distinguish between erosion resulting from fracturing or from chemical alteration. Calipers commonly used in commercial practice to measure the size of a borehole have either two or three independent arms; it is clear that to measure the orientation of a fracture plane, three independent measurements are necessary. LASL has built and fielded a high temperature (200°C) oriented caliper with three independent arms that are capable of resolving changes of 0.2 mm in radius. The LASL tool is about five times more sensitive than commercial tools.

An example of the type of fracture mapping data obtained from a three-independent-arm-caliper is shown in Figure 5.2, which is an isometric replot of standard logging data. The existence of a fractured zone about 0.5 to 0.7 feet wide cutting across the borehole is easy to visualize from the isometric plot, as is the dip and the strike. Because a good visual display often enhances the usefulness of many types of data, we believe that caliper data intended for fracture mapping should be plotted in isometric form rather than in the standard form used by commercial logging companies. To do so requires only a straightforward computer plotting routine. The improvement in the visualization of fracture planes afforded by the isometric plot is clearly illustrated by comparing Figure 5.2 of this report with Figure 6.1 of Reference 24. The value of the isometrics is made even clearer when it is realized that Figure 6.1 of Reference 24 is plotted with an inverted depth scale, i.e., distance increases from the bottom of the wellbore to the surface; the orientation of the fracture plane indicated by the isometric plot makes all depth and angular relationships quite clear.

When data from a two-independent arm caliper are all that are available, no more than a rough indication of whether fractures have a shallow or steep dip can be obtained. An indication of a steep dip will be qualitatively correct, but an indication of a shallow dip may be misleading for it may arise

Figure 5.2. Isometric replot of LASL three-independent-arm caliper data. The fracture plane, dip, and strike are readily visualized when data are plotted in this manner. LASL data at 8920 feet in hole GT-2B /23/. The erosion patterns are drawn with an exaggerated scale in the radial direction.

from a pathological case in which the caliper arms see two eroded points at the same elevation in the same quadrant, but miss the low (or high) eroded point. In principle, the trace of the fracture plane should be detectable, but in practice, it may be overlooked. For the purpose of interpreting two-arm caliper data in this review, we assume that the pathological case is rare and that most indications of shallow dip do, in fact, arise from nearly horizontal weakness planes. An example of raw, two-independent-arm unoriented caliper data with fracture location and estimated shallow or steep dip angles is shown in Figure 5.3. The results of interpreting commercial two-independent arm caliper data over an 1800-foot interval from 2500 to 4300 feet in hole GT-2B at Fenton Hill are shown in Figure 5.1.

Figure 5.3. Dresser Atlas two-independent-arm caliper log of a portion of GT-2B modified to illustrate inferred fractured locations and estimates of shallow or steep dips /25/.

5.2.2 Electrical Properties Logs

Water in contact with rock will contain dissolved salts and act as an electrolyte, eventually attaining a conductivity of up to several S/m. Because fractures in hard rock provide most of the permeability, the fluid-filled fractures are relatively good electrical conductors in comparison with the adjacent low porosity rock. Several different types of tools make measurements based on the conductivity of the medium (the rock and fluid) in the immediate vicinity of a borehole. Historically, tools that measure the d.c. or low frequency conductivity of the medium have been called electrical tools. The measurement requires a continuous conducting path extending outward from the tool electrode into the formation and back to the return electrode. Another class of tools, which is referred to as induction tools by the logging industry, use high frequency inductive circuits to make measurements within the formation without requiring a continuous conducting path. A third type of measurement senses the voltage that arises from electrochemical and electrokinetic forces. This is the spontaneous potential method (SP). The SP log will be reviewed first because it is commonly used by the logging industry, although it does not appear particularly useful for locating natural fractures. Electrical and induction tools will then be discussed. Although induction logs have been highly developed in recent years, it appears that a specialized electrical tool--the resistivity dipmeter--is especially useful for locating fracture intercepts at the borehole.

5.2.2.1 Spontaneous Potential Log

The spontaneous potential or SP log is a recording versus depth of the potential difference between an electrode moving in the borehole and a fixed electrode placed at a distant location, usually the ground surface. The differences in potential are thought to be related to differences in ionic activity throughout the formation and to "streaming" potentials produced by the flow of electrolytes through the rock pores and fractures. Typically, there is not a direct observable relation between SP deflection and fractures, porosity, and permeability /26/. Based on many years of empirical development in the petroleum industry, the logs are useful for distinguishing sandstones and shales and are often run as part of other geophysical logs to

assist correlations and interpretations of other logs. This experience, however, is not directly transferrable to geothermal logging in hard rock.

The SP records at Fenton Hill indicate no significant sensitivity to fracture location prior to hydraulic fracturing, as illustrated in Figure 5.4.

5.2.2.2 Electric Logs

Electric tools vary mostly in the number and location of electrodes. The design configurations depend primarily on whether the purpose is a vertical or a lateral or an omnidirectional investigation, or shallow or deep sensing beyond the wellbore. The different designs are reviewed in some detail in Reference 26, where the emphasis is on tool operation in strata of interest to the petroleum industry. We shall not duplicate that work, but rather shall extend it to examine the ability of tools to locate fractures in hard rock. Before proceeding, however, certain tool names and trade names will be defined. Two of the earliest logs used by the logging industry as part of a conventional electric survey rely on the normal and the lateral resistivity tools. The normal tool injects current between an electrode on the sonde and the uninsulated portion of the cable armor, which is some distance from the sonde. One measuring electrode is located on the sonde, and the other is on the insulated portion of the cable. The spacing between injection and measuring electrodes is normally 16 inches or 64 inches. For specialized logs, an ultra-long spacing ranging from 75 to 1000 feet is used. The lateral log has both current injection electrodes on the sonde. The spacing between the midpoint of the injection electrodes and the measuring electrode is 18' 8". To provide better definition of the measurement region than is afforded by the normal and lateral tools, focusing or guard electrodes are employed to control the potential distribution and the current paths in the ground. Several different types of Laterologs (a Schlumberger trade name) produce a relatively narrow transverse current beam. For example, the approximate thickness of the current sheet produced by a Laterolog 7 is 32 inches, that of the Laterolog 3 is 12 inches, and that of the Laterolog 8 is 14 inches. Not only does current from the Laterolog 8 not extend as far from the borehole as does that from the Laterolog 7, but in an orthotropic

Figure 5.4. Spontaneous potential log in hole EE-1 at Fenton Hill prior to hydraulic fracturing. No natural fractures are apparent /27/.

medium, the response of the Laterolog 8 is more dependent upon the component of conductivity parallel to the borehole. A Dual-Laterolog employs yet two other variations of the focused electric log which simultaneously provide both deep and shallow penetrations. As the name implies, the spherically-focused log produces spherical equipotential surfaces. Without guard electrodes, the borehole would distort the current paths making data interpretation difficult. The Microlog (also a Schlumberger trade name) uses small electrodes on a pad to sample a small region, while the Microlaterolog is a laterally-focused version of the Microlog. With the jargon of the trade defined, we proceed to review electric tool operation in hard rock.

Fracture Identification from Electric Logs

The diplog--an oriented, four-independent-arm microlaterolog device--is of particular interest for its apparent usefulness in fracture mapping. Attached to each arm are current injection and potential measurement electrodes in pads that contact the wall. This close-spaced resistance measuring tool details both minor and major zones that are permeable to fluids in the borehole wall. The pad electrodes produce four traces at each quadrant of the borehole with resistivity changes at permeable zones appearing as spikes on each trace. If the resistivity spikes can be reliably correlated between the four records, then a permeable plane can be identified, and the orientation can be calculated for the strike and dip of an identified plane. Generally, the correlations and determinations of orientation are made with service company computer programs originally developed for the petroleum industry. However, programming dip calculations for bedded strata is, at present, considerably more reliable than programming for the much less systematically oriented fractures. Almost assuredly, no existing program is adequate for producing dependable answers. Thus, computer-reduced displays of fractured basement rock may contain considerable error, even though the raw data are very accurate. Scott Keys of the U.S.G.S. has confirmed this difficulty after observing poor correlations between computerized diplog output and the data obtained from the sonic televiewer /28/.

Figure 5.5 is a sample of four diplog traces indicating a varying resistivity with depth in GT-2. A portion of the log is shown where a correlation appears to exist and where the record is relatively simple. Because an accurate diplog correlation algorithm has apparently not been devised for hard rock, we have attempted a very simple method for locating fractures and compared the results with a caliper log. The raw diplog resistivities were combined by summing the values of the less resistive areas recorded by the four pads and plotting these values on the corresponding caliper log. Figure 5.6 shows a sampling of the GT-2 caliper log cross-plotted with the summed relative resistivity values. Also shown are the approximate locations and indicated relative dips for the fractures. Note that about a four foot depth correction is needed to bring the correlation between the diplog and caliper log into better alignment. It is believed that the depth inconsistency has arisen more from the depth logging than from the reduction of the caliper and diplog traces. To wit, the caliper measures features directly at the borehole wall. The spacing between electrodes on a Microlog is of the order of one inch; thus, the diplog samples a volume of rock with a characteristic height of no more than a few inches. The offset between a caliper and a diplog should be less than a few inches at most--not several feet. The need for a depth correction when trying to interpret logs is a disturbing aspect of the analysis which occurs all too often as will be seen in subsequent subsections. The apparent depth inconsistency is emphasized because it is a problem that can be solved in a straightforward manner both by improved data taking and improved hardware, as indicated in Subsection 5.2.9.

The diplog seems to have consistent and reliable traces from a depth of 5786 feet (near the top of the log) to about 6160 feet. After that, the records do not correlate as well with the indicated weaknesses on the caliper log. The log was terminated at 6460 feet, even though the hole was open to 8960 feet. Whether or not the diplog would perform well at depths to 9000 feet is not known with certainty, but considering the fact that a Laterolog was used to this depth, there is no fundamental reason for not expecting the diplog to be useful. The Laterolog record is shown in

Figure 5.5. Portion of the four-independent-arm diplog resistivity survey in GT-2 on 12/17/74 showing tentative fracture plane correlations of the 4 traces. Pads 1, 2, 3, and 4 are on successive quadrants.

Figure 5.6. Sample diplog and caliper-log correlation showing approximate fracture locations. Based on Dresser-Atlas data obtained at Fenton Hill in hole GT-2 on 12/17/74 (diplog) and 2/11/72 (caliper). The correlation is improved by offsetting logs four feet.

Figure 5.7. This record is consistent with the corresponding caliper log (Figure 5.3) if a depth correction of about 4 feet is made.

Figure 5.7. Focused resistivity log (Laterolog) obtained at great depths in hole GT-2B at Fenton Hill /25/.

The diplog appears to be a very useful tool for mapping borehole fracture intercepts. Two reservations in our recommendations for its use are (1) the diplog apparently was not used below 6460 feet, and (2) the correlations between diplog and caliper decreased below 6160 feet. Additional diplog experiments are warranted.

The resistivity records taken at Fenton Hill include not only the micro-spacings of the diplog, but the standard source-receiver spacings of 16 inches, 64 inches and 18' 8" as well. With increased spacing, the resistivity electrodes investigate farther from the borehole but cannot locate individual fractures or permeable zones. The record from a short normal log, Figure 5.8, is rather diffuse and does not define isolated fracture planes.

Fracture Identification from Induction Logs

The laterally focused induction log is a special tool that was originally developed for sites where nonconducting oil-based muds had to be used, for example, to stabilize weak clay zones, but induction devices also work with borehole fluids having a low to moderate conductivity. The operating principle is based upon the sensing of eddy current fields induced in a conductive medium. The measured signal is proportional to the conductivity of the medium surrounding the sonde. Focusing is used to minimize the effects

Figure 5.8. The Schlumberger Induction Electric Log showing short normal, induction resistivity and conductivity traces in Hole EE-1 at Fenton Hill. Over the interval 6420 to 6870 feet, there are twenty-one regions of increased conductivity and twenty-eight zones of caliper offset. Seventeen zones of increased conductivity and caliper offset correlate with one another. A one-to-one correspondence between amplitudes in the conductivity and caliper logs does not exist. The normal electric log is too diffuse to be useful. The conductivity and induction resistivity plots are the inverse of one another. (The induction resistivity plot is faint in the original field log and does not reproduce well.) The corresponding SP log is plotted in Figure 5.4.

of borehole fluids. When induction-logging devices are used with source and receiver coils oriented both parallel and perpendicular to the axis of the sonde, it is also theoretically possible to determine formation dip. Values of horizontal and vertical conductivities can, in principle, be derived from the measured values, but in practice, anisotropy greatly complicates the responses of induction as well as direct current and alternating current electrode borehole logging devices /29/.

One run of an induction log for depths of 6420 to 6880 feet in EE-1 (which was repeated three times for validation) is shown in Figure 5.8. Spontaneous potential (SP), short normal, induction resistivity and conductivity traces were all recorded from the single sonde (the SP trace is shown in Figure 5.4). Because the conductivity trace is shown at a small scale, relative values and peaks are poorly resolved. The induction resistivity record is the inverse of the conductivity record, but the resistivity record is faint and consequently difficult to interpret. However, twenty-one locations of increased conductivity are identified in Figure 5.8. Of these twenty-one, seventeen are identified as fractures based on a correlation with hole erosion patterns on the corresponding caliper log.

5.2.3 Acoustic Televiwer Log

The televiwer is an acoustic device that produces a picture that images the elastic properties of the borehole surface. It is thus able to see cracks, offsets, and zones of varying acoustic impedance. The televiwer is the U.S. Geological Survey high temperature version of the commercial seisviwer. The operating principle of the televiwer is as follows: A narrow acoustic beam is emitted from a rotating transmitter to scan the borehole surface. Irregularities on the borehole wall cause the reflected signal to vary in intensity. The amplitude modulated acoustic signal is then used to produce an intensity-modulated display on a cathode ray tube. A coherent picture is produced by synchronizing the display with the rotating transmitter. The signal frequency is in the one to two megahertz range to allow a resolution of approximately one millimeter. The pulse repetition rate is approximately one kilohertz, and the transmitter rotation rate is 3 rps /30,31/.

As is the case with most sophisticated tools, the televiewer is limited by temperature. A dewar protects electronics to a down-hole temperature of approximately 260°C, but it appears that the operation of the magnetic orientation device may have been unreliable on some tests. The technique of acoustic imaging makes the tool complementary to several other logs, especially the caliper and television, which operate on different principles. Televiewer data have proven especially useful in several parts of Fenton Hill boreholes /25/. However, the televiewer system is generally not a feasible method for logging an entire borehole because a slow logging rate (about 6 feet/min) makes the traverse expensive. Nonetheless, the tool appears to be extremely useful for confirming the presence of fractures and measuring their size and orientation.

5.2.4 Television

Borehole television has been used as an inspection device on several underground tests, and more importantly, for the present purpose, it has been used not only to detect permeable gas bearing fractures intersecting boreholes in shale /32/, but also to locate borehole-fracture intercepts in granite /33/. Based on the experience gained in shale during the coal degassification project, it is believed that borehole television could be used to resolve uncertainties in interpreting caliper and televiewer data. Permeable fractures were located in the coal degassification program by scanning the borehole for signs of fluid turbulence caused by gas injection. Although we are getting a little ahead of our story, we note that efflux points between boreholes could be mapped by a similar technique, provided the borehole fluid contained a small number density of particulates to make flow visualization possible. Prior to its use in a geothermal reservoir, a television camera would require thermal hardening. The expense of doing so, however, makes it prudent to first examine the feasibility of using downhole photography.

5.2.5 Impression Packer

In principle, special inflatable packers made of rubber-like material can be inserted in a borehole to provide a three-dimensional molded record of the borehole surface. The molded impression can be used to confirm the existence of fractures and to determine their size and orientation. In

practice, the use of this conceptually simple device has not always yielded good results. The impression packer was found to be unsatisfactory for fracture mapping at normal temperatures in the Wattenberg Gas Field north of Denver, Colorado /33/, perhaps because of relatively soft sedimentary rock formations. At elevated temperatures in the Fenton Hill reservoir, special impression packers rated at 200°C failed at 150°C. Surprisingly, ordinary packers of the type used to seal-off sections of wellbore proved capable of retaining impressions and were so used at Fenton Hill /35/. The main uncertainty in the use of ordinary packers at the 150°C temperature range is associated with the unreliable operation of magnetic orientation sensors. The effective use of impression packers in a hard, hot rock requires improved high temperature capabilities.

5.2.6 Acoustic Logs

In single hole acoustic logging, the basic procedure is to transmit a sonic wavetrain ($5 < f < 15$ kHz) from a sonde out into the formation and to listen for the direct transmitted wave and reflected waves at a receiver several feet away on the same sonde. Although the hardware of different manufacturers may differ in a number of ways, e.g., receiver Q, center frequency, pulse shape, isolation of receiver from transmitter, and the number and spacing of transmitters and receivers on a single sonde, we shall not examine hardware in detail, but rather will concentrate on reviewing four principal data analysis techniques that have been used with varying degrees of success in locating fractures. The methods are: (1) cycle skipping, (2) amplitude reduction, (3) waveform analysis, and (4) phase splitting. The basic procedures were introduced about twenty years ago, but the complexity of acoustic wave interactions with geologic formations and what appears to be a lack of active research have conspired to prevent any one of the techniques from unambiguously locating fractures. At the present time, the logs are perhaps most useful simply because they provide what a log analyst calls "correlatable features," i.e., a distinct irregularity in the record that at least in some cases can be related to fractures.

5.2.6.1 Cycle Skipping

Cycle skipping is an effect observed with the interval transit time (Δt) sonic log. The sonic tool usually employs one transmitter above and one transmitter below two pairs of receivers to effect a partial compensation for borehole irregularities and sonde tilt. The spacing between a transmitter and its nearest receiver is of the order of several feet, and between pairs of receivers about half the transmitter-receiver spacing, e.g., a typical Dresser-Atlas BHC Acoustilog has a transmitter-receiver spacing of four feet and a receiver-receiver spacing of two feet. The log is customarily used to record the reciprocal of the formation P-wave velocity parallel to the sonde by averaging the transit times measured by each set of receivers. Time interval measurements are made by setting voltage trigger levels that correspond to preselected P-wave amplitudes.

If the acoustic path between the transmitter and receiver encounters fractures, then the first arriving signal may be so attenuated as to be incapable of triggering the timing circuits in either of the two receivers. Rather, a higher amplitude signal later in the wave train will cause triggering, resulting in an abrupt and clearly anomalous increase in the recorded time interval measurement. The discontinuity in Δt arises from what is referred to as a cycle skip. The relationship between P-wave amplitude reduction and fracturing is complicated /36/, so that a simple adjustment of triggering levels to provide a unique indication of fracturing is apparently not possible at the present state-of-the-art. Based upon experimental evidence gathered in hole GT-2B at Fenton Hill, cycle skips were frequently recorded, but their locations were not reproducible over the interval 8500 to 8900 feet. The raw data from 8700 to 8800 feet are shown in Figure 5.9 for three different runs.

When all of the cycle skips were combined in a single record, their locations correlated with irregularities indicated by a two-independent-arm caliper. Note that the record not only exhibits increases, but also decreases in Δt . A decrease following an increase might be explainable as arising from circuit overload recovery were it not for an occasional solitary spike indicating a decrease in Δt . This anomalous behavior requires a detailed analysis of circuit operation.

Figure 5.9. Cycle skipping observed on a Δt log in hole GT-2B at Fenton Hill. Three different logging runs over the same depth interval indicate that cycle skipping is not reproducible. Log run on 8/12/78.

5.2.6.2 Amplitude Reduction

Historically, the phenomenon of cycle skipping was recognized through observation of field logs taken for the purpose of determining formation P-wave velocity. For detecting fractures, researchers decided that the more fundamental approach of directly recording the amplitude of both the first positive compressional wave and first positive shear-wave (or borehole-surface wave) would lead to more useful results than a technique that depended upon the uncertain settings of gain controls. Thus, the amplitude reduction log consists of a plot of wave amplitudes versus depth, which can be obtained, for example, by using a sample-and-hold boxcar circuit. Theoretical, laboratory, and field studies have shown that an amplitude reduction is experienced by a P-wave as it crosses a fracture having a steep dip with respect to the borehole. Theory indicates that a maximum reduction occurs for dip angles between 33 and 78 degrees. Of particular interest for logging from vertical boreholes in a deep geothermal reservoir, theory predicts that the attenuation decreases rapidly for dips greater than 78 degrees, with no attenuation of P-waves for exactly vertical fractures /36/. S-wave amplitudes suffer their greatest reduction in amplitude when crossing fractures that are nearly perpendicular to the borehole /36/.

Based on work performed by Schlumberger in limestone /36/, the reduction in P-wave amplitude within a region known through core recovery to contain "near-vertical" fractures is illustrated in Figure 5.10. The core samples were not analyzed with precision so the dip angle associated with the term "near-vertical" is not known. (It would be of great usefulness to know if the dip exceeded 78 degrees.) The core did not extend into the region characterized by a sharp decrease in S-wave amplitude, Figure 5.10, therefore, the existence of near-horizontal fractures cannot be confirmed.

Several factors other than fractures also reduce sonic amplitudes. In a hot dry rock reservoir, these factors include poor tool centralization, hole size variation, and borehole rugosity. The wavelength of a 15-kHz sonic wave in a borehole fluid (water) is only four inches. Roughly speaking, a two inch eccentricity would give complete destructive interference between waves on opposite sides of the borehole resulting in a sharp decrease in

received amplitudes. A one-quarter inch offset is reported to result in a 50 percent decrease in amplitude /36/. Hole size variations lead to interference effects, while borehole roughness scatters waves leading to a reduction in intensity. Most of the research on amplitude reduction for fracture detection appears to have been carried out circa 1963. At that time, it was felt that no conclusive results had been reached concerning the advantage of signal attenuation measurements over straight amplitude logging (waveform recording). Apparently, little has changed during the intervening years.

Figure 5.10. Schlumberger record of a confirmed vertical fracture reducing the compressional wave amplitude and a suspected flat angle fracture affecting the shear wave amplitude /36/.

5.2.6.3 Waveform Analysis

The waveform record of a received acoustic pulse is the most fundamental of the acoustic logs. It contains all of the information regarding elastic wave propagation in the formation, i.e., it is a complete set of amplitude and phase data. Decreases in amplitude that gave rise to cycle skipping and dips in the amplitude log can be detected by analysis of the waveform. Interference effects arising from reflections can be detected as changes in amplitude or phase.

A portion of a waveform log (Dresser-Atlas Signature Log) between 8700 and 8800 feet in hole GT-2B at Fenton Hill is shown in Figure 5.11. The logging tool employed a six-foot and a four-foot spacing between the transmitter and receiver. The two spacings correspond to the spacing used in the Δt Acoustilog. The waveforms are, in fact, the raw signals that are used to generate a Δt log (although the data of Figure 5.11 were not taken during the same logging run as those of Figure 5.9). With appropriate data manipulation, the waveform log can be used to produce the other three logs discussed in this subsection.

Qualitatively, one can observe that the region of heavy cycle skipping between 8750 and 8770 feet, Figure 5.9, is marked both by phase shifts and amplitude variations, Figure 5.11. Depending upon the details of the Δt logging circuitry, both the phase shift and amplitude reduction can produce cycle skipping. The state-of-the-art has not yet reached the level of sophistication that allows fractures to be located unambiguously and with high confidence from waveform analyses.

5.2.6.4 Phase Splitting

Instead of viewing amplitude versus time waveforms, it is possible to produce an entirely different type of record that enhances the visual perception of phase shifts. The waveform display of Figure 5.11 was produced by displaying signal amplitude versus time on an oscilloscope and then recording successive cathode ray tube (CRT) images on a continuous strip of 35 mm film. By disconnecting the vertical amplifier from the vertical deflection plates and then using the vertical output to modulate a control grid in the CRT, a straight-line, intensity modulated display is generated to represent the acoustic signal. The commercial techniques produce a faint spot with a zero voltage waveform, a spot intensity which increases with increasing positive voltage, and beam cut-off (no spot) for all negative voltages. A recent innovation at the Lawrence Livermore Laboratory is to color modulate the display. The utility of this new scheme is still being evaluated by its developers /37/. With the proper exposure, the images of successive intensity modulated sweeps blend together to form a continuous display of alternating

Figure 5.11. Waveform log (Dresser-Atlas Signature Log) in hole GT-2B at Fenton Hill. The amplitude reduction and phase shifts between 8750 and 8770 feet correspond to the cycle skips in Figure 5.9.

dark and light bands. In a homogeneous medium, the record consists of uniform dark and light bands running parallel to the borehole. In an inhomogeneous medium, the banding is irregular, and it is the irregularities which are interpreted to indicate fracturing and lithologic variations. The commercial logs are trade named Variable Density Log or VDL (Schlumberger), Micro-Seismogram (Welex), and 3-D Log (Birdwell).

The interpretation of the logs is not straightforward; we feel that at the present state-of-the-art many of the irregularities in the records must fall into the category of "correlatable features." For example, data taken in limestone, Figure 5.12a, illustrate the phenomena of phase splitting which has been associated with vertical fracturing. Note that at 1080 ms and at 30 feet above the location marked B, the dark band splits and then rejoins at location B. Because this phase splitting occurs without any appreciable change in time of the first arrival, Welex log analysts believe that the phase split results from the signal on one side of the borehole being out of phase with that from the other side. Because of the long interval over which the split occurs, they have deduced that the cause is a fracture or other large discontinuity more nearly vertical than horizontal /38/, but they did not deduce the distance of the discontinuity from the well. To complement the phasing information of the Micro-Seismogram, an amplitude reduction curve (called a Fracture Finder by Welex) is also displayed. When taken during the first positive pulse, the amplitude is that of the P-wave; when taken near the first direct S-wave arrival, the curve can be contaminated with P-wave returns from reflections at some distance from the well. The plot in Figure 5.12a is termed the S-wave amplitude. Within the phase-split interval, the signal amplitude is not reduced as much as it is at the ends of the interval. A significant S-wave reduction from vertical fractures is not expected as discussed in Subsection 5.2.6.2. and thus, it is believed that an adequate data display must include a P-wave Fracture Finder. Whether the phase split is caused by a P-wave returning from a fracture at some distance from the wellbore and interacting with the

(a) MICRO-SEISMOGRAM LOG IN FRACTURED MISSISSIPPIAN

(b) VERTICAL FRACTURE IN LIMESTONE

Figure 5.12. Phase-splitting technique using Micro-Seismograms and acoustic amplitude log (Fracture Finder). Tests performed in limestone /38/.

(a) Vertical fracture inferred from phase-split at $t = 1080$ ms ranging from B to 30 feet above B.

(b) Vertical fracture verified by core indicated by phase splits, phase irregularities, and dip in acoustic amplitude log at indicated location.

direct S-wave is not known. The amplitude curve of Figure 5.12a does not appear useful for locating the fracture inferred from the Micro-Seismogram. That a fracture did, in fact, exist at some distance from the wellbore was not determined by independent means.

A case where vertical fracturing was observed from a core is illustrated in Figure 5.12b. In this case, the fracture cut across the wellbore. Phase-splittings are clearly evident on the Micro-Seismogram at the location indicated, as are a number of other well defined interference effects. The amplitude reduction curve is not identified as either a P-wave or S-wave, but it too clearly indicates a fractured zone.

An example of phase splitting observed with a Variable Density Log (VDL) at hole GT-2B at Fenton Hill is illustrated in Figure 5.13. Distinct phase-splits occur near 8740, 8768, 8790, and 8805 feet, and at several times from the onset of the first direct P-wave arrival. The orientation of the fractures and their distances from the wellbore are uncertain. Without an underlying theoretical analysis and an extensive catalog of experimentally verified VDL patterns, it is not possible to infer the details of fracture geometry with a high confidence level. The simplest interpretation of Figure 5.13, based upon the logs of Figure 5.12, is that the fractures are near-vertical and intersect the wellbore at the indicated depths. Additional support for this simple interpretation comes from a core sample which verifies the fracture at 8740 feet /39/. We believe that considerably more work must be done before the phase-splitting technique can be justified for fracture mapping.

5.2.7 Radiochemical Logs

The contact surfaces between different rock types are often susceptible to erosion when cut by a borehole. To differentiate between erosion arising at a fracture and at a contact alteration, both of which appear the same to a caliper, it is necessary to sense the chemical properties of the rock. Geochemistry and petrology are extensive subjects which we shall not dwell upon; for logging purposes, we merely note that chemical differences between rocks arise from metamorphism, crystallization, diffusion, hydrothermal alteration, and fractionation. Thus, logs which sense major and minor element concentrations help to identify rock units and interpret various fracture-sensitive logs. The most common tool is the gamma ray log, which integrates the

Figure 5.13. Dresser Atlas Variable Density Acoustic Log (VDL) of a portion of hole GT-2B interpreted to locate fractures by phase shifts. Phase shifts occur near 8740, 8768, 8790, and 8805 feet. Log run 6/14/77.

total background gamma radiation emitted from the rock. More chemically selective is the spectralog, a tool using radiation spectral analysis to sense radioactive potassium, thorium, and uranium. A third is the silicon/calcium log, which employs pulsed neutron sensing. A correlation of chemical variations with caliper log indications of hole erosion can distinguish weak zones indicating dikes and changes in rock type from fractures within given rock units.

All three chemical sensing logs--gamma ray, spectralog, and silicon/calcium--were recorded at Fenton Hill. Figure 5.1 illustrates a portion of hole GT-2 where logs sensitive to rock chemistry were used to supplement the chip log and to locate dikes (igneous intrusive tabular bodies). The qualitative variations in silicon content derived from the silicon/calcium log are shown as relative concentrations. The dikes of low-silicon content seem to have been injected in such a way that chemical alteration occurred. Dikes are commonly confined by old fractures, often associated with a weakening of both the injected and bounding rocks by hydrothermal fluids. The weaknesses are recorded as washouts by the caliper log. Once a depth correction of about 6 to 10 feet is made between the silicon/calcium and the caliper logs, these zones of lower silicon content often correspond with symmetric hole erosion indicated by the caliper logs, Figure 5.14. This method of locating rock units is more accurate than the chip log and can precisely pinpoint unit boundaries, particularly those of dikes and other thin rock units.

Abnormally high total gamma radiation measurements were also plotted to aid in determining the lithology and to seek a correlation between gamma sources and fractures. Gamma spikes appear to occur in thicker rock zones of constant silicon content and rarely show signs of contact alteration between rock units. The spikes in Figure 5.1 are interpreted as representing either a localized crystallization band of trace elements within a major rock unit or as a fracture where trace elements have condensed out of fluids moving through the fracture. Based upon spectralog data, the dominant radioactive trace element is uranium. Only occasionally do gamma

Figure 5.14. Comparison of silicon and caliper logs in zone of heavy contact alteration. Note 6 to 10 foot offset in depth scale needed to improve correlation between logs. Zones of low silicon and enlarged diameter interpreted to be dikes and contact alterations. Zones of borehole erosion without prominent silicon content interpreted to be fractures. Fracture location and size indicated by F2 or F4 (see Subsection 6.1 for definitions). Dikes and contact alterations indicated by CA,3 (see, also, Subsection 6.1).

spikes correlate with fracture locations inferred from the caliper log as indicated in Figure 5.1. The silicon/calcium and gamma ray logs were found quite helpful in identifying rock contacts and zones of chemical alteration of the rock. However, no chemical indicator seemed to correlate closely with fractures.

5.2.8 Formation Density Compensated Log

The formation density compensated log is used mainly as a porosity logging tool in the petroleum industry. Whether or not a commercial tool is sensitive enough to detect borehole fracture intercepts or accurate enough to measure fracture porosity is addressed in this subsection by examining field logs.

Using a cobalt 60 source, the density logging tool emits gamma rays in the 1 Mev range that collide with the orbital electrons of the formation elements and are scattered principally through the Compton effect. A crucial aspect of the tool design is the two detectors and compensating circuits that are used to make a correction for the effects of mudcake and borehole rugosity. The backscattered rays that reach the main detector, which is spaced about two feet from the source, are counted and related to the rock density through a knowledge of the scattering process and the atomic properties of the elemental constituents of the rock. The value of the density is inaccurate because of failure to account for the thickness and density of borehole fluids interposed between the tool and the formation. A density correction, computed using the signals from the main detector and the secondary detector, which is spaced about one foot from the source, is applied to the uncompensated value derived from the main detector. Intuitively, it can be appreciated that by employing two detectors, one that sees a long path through the formation because it is spaced away from the source, and one that sees only a short path through the formation because of its close spacing to the source, effects near the borehole can be eliminated from the final result. The total depth of investigation is limited to about seven inches into the formation. It is clear that the accuracy of the correction must depend upon each detector being spaced the same distance from the borehole wall, i.e., sonde tilt or surface

irregularities will reduce the accuracy of the compensation. Under average operating conditions, presumably meaning a smooth borehole, the standard deviation of a compensated tool is of the order of 0.01 to 0.015 gm/cc /40/.

The ability of the formation density compensated log to detect fractures can be evaluated by comparing the density log with a caliper log. A Dresser-Atlas Compensated Densilog between 8600 and 8800 feet in hole EE-1 at Fenton Hill is shown along with a two-independent-arm caliper log in Figure 5.15. Borehole erosion patterns from the caliper log at 8694, 8699, 8718, 8727, and 8732 feet match irregularities in the formation density log to within about two feet, although the density log feature at 8712 feet is quite weak and almost surely would not be associated with a fracture if it were not for the caliper log. The inverse process of picking fractures from the density log and matching them with caliper erosion zones does not work well. The prominent pulse at 8687 feet on the density log occurs within a region of the caliper log which appears relatively smooth. Because the density and caliper logs fail to correlate at 8687 feet, and because the density correction is negative, we are led to believe that the apparent large decrease in density is an artifact which may have arisen from tool tilt. An example of density log artifacts--large non-reproducible excursions of the measured density--is shown in Figure 5.16 for a logging run made in an enlarged and rugose shale borehole.

Taken at face value, the density log yields the following fracture porosities at the six aforementioned depths, based upon grain density of 2.60 gm/cc: 0.130, 0.064, 0.061, 0.026, 0.034, 0.076, and 0.091. The grain density of 2.60 gm/cc is a value consistent with the density log between 8600 and 8670 feet, and the in situ matrix porosity of 0.001 derived from laboratory tests /24/. The density log implies an even smaller value of the grain density (2.55 gm/cc) between 8670 and 8800 feet; both values are less than that usually associated with granite (2.66 gm/cc) and raises a question about the accuracy of the density log. The inferred fracture porosities are considerably greater than the 0.001 in situ matrix porosity. The value of 0.130 appears to be associated

Figure 5.15. Comparison of compensated formation density log (Dresser-Atlas Densilog) with two-independent-arm caliper log in hole EE-1 at Fenton Hill. Fractures inferred from caliper log correlate with pulses in density log to within 2 feet, but the inverse does not hold. The large Densilog spike at 8687 feet is believed to be a spurious signal arising from tool tilt. Densilog run 9/28/75, caliper log run 9/27/75.

with a spurious response; establishing the validity of the other measurements requires, in our opinion, calibration tests in a medium of known fracture porosity.

Figure 5.16. Non-reproducible artifacts on formation density compensated log in shale caused by borehole enlargement and rugosity /40/.

5.2.9 Depth Measurement Offsets

The elimination of depth uncertainties when crosscorrelating logs requires a precision of the order of 0.02 percent, i.e., it is believed that a depth accuracy of ± 1 foot near the bottom of a geothermal well is needed for relating sharply defined features, such as fractures, from one log to another. This high degree of precision requires that the cable reel

be accurately calibrated and that corrections be made for thermal expansion and elastic stretch. For example, a change in the mean temperature of the borehole of 25°F, which can easily occur if logging runs are made at different times and under different operating conditions, will result in a change in cable length of between one to two feet (depending on cable alloy) at a depth of 8000 feet. The required precision appears to be greater than most logging service companies are accustomed to, as evidenced by their standard logging records. Although more detailed record keeping concerning reel calibration, sonde weight, borehole temperature, and cable specifications would reduce uncertainties, it is believed that depth uncertainties could almost assuredly be greatly reduced by installing a fiducial ring as a means of referring all measurements to a fixed depth in the borehole. The device could be an attachment at the bottom of the drill hole casing. Identifiers attached to the ring--such as a caliper offset, radiation source, magnetic source, and an electrically conductive sleeve--would enable each log to self-record a depth measurement based on a common, fixed reference point. The use of hardware to provide a common depth reference is appealing because it is essentially fool proof.

5.3 LOGGING DURING POST-HYDRAULIC FRACTURE OPERATIONS

In a reservoir of economic size, it is almost certain that a series of steeply dipping hydraulically induced fractures will form the heat transfer surfaces and that the fractures will be cut by two near-horizontal wellbores. To ensure that the wellbores are essentially perpendicular to the heat transfer surfaces, the strike of hydraulically induced fractures must be known in advance of directional drilling operations. One method for satisfying this requirement is to create a hydraulic fracture in a still vertical wellbore just above the intended operating depth and then to measure the orientation of the fracture with an appropriate tool, as discussed in Subsection 5.2. The measurements are limited in working depth only by the maximum operating temperature of logging tools and are limited in accuracy by possible variations in strike with distance from the borehole. The latter limitation needs to be investigated with long

range mapping methods, such as radar (Sections 2 and 3), and with theoretical analyses. A second method, which does not depend upon borehole tools and appears potentially useful, is to determine the average strike of a hydraulic fracture using surface tilt measurements. At the present time, the tilt technique has been demonstrated to depths of 10,000 feet. The method is reviewed briefly in Appendix A.

The second application of post-hydraulic fracture mapping is to locate and determine the orientation of possible well interconnections. The techniques discussed in Subsection 5.2 can also be used to locate hydraulically induced fractures. In most cases, the locations of induced fractures are known from the position of straddle-packers used in the fracturing operation, so a greater emphasis is placed on determining fracture orientation and size. The strike and dip can be determined in principle with a televiewer, television, three-independent arm caliper, four-independent-arm resistivity dipmeter, and impression packer. In practice, high temperatures restrict their use. Fracture size can be estimated using several other techniques which depend mainly on the fluid flow or heat transfer properties of a fracture. With a single borehole and a blind fracture, all fluid flow processes are inherently unsteady; namely, the fracture must be inflated at high pressure and then be allowed to collapse at reduced pressure. The logs which work under these conditions are (1) temperature, (2) flow meter, and (3) tracer. These three techniques are evaluated in the following subsection. Television, discussed in Subsection 5.2.4, might be practical for detecting fluid mixing at fracture sites if the borehole fluid contained enough particulates to make flow visualization possible, while still retaining sufficient optical clarity.

5.4 LOGGING DURING TWO-WELL COMPLETION

The most fundamental way to map fracture connections between wells is by flow testing. The main emphasis is on determining the location and flow capacity of fractures. The techniques involving the use of temperature probes, flow meters, and radioactive tracers are reviewed in this subsection.

5.4.1 Temperature Logs

Although the temperature level is needed for estimating the capacity of a geothermal reservoir, a logging tool that records the temperature difference between two sensors is more capable of detecting flow locations at low fluid flow rates than one that measures the temperature level with the same type of transducer. A conventional temperature log and a caliper log run over the same interval in borehole CH-3 at the Raft River Geothermal Reservoir /41/ are compared in Figure 5.17. The correlation between apparent flow entries and the two major hole enlargement (fracture) portions of the caliper log is quite good. The differential temperature measurements were accomplished using two sensors spaced two feet apart on a sonde. The differencing was accomplished numerically. The accuracy of the temperature measurement was not reported, i.e., the separate temperature measurements corrected for the two-foot offset was not compared for the two transducers.

At Fenton Hill, single-transducer temperature logs have been used to infer flow conditions at well-to-well fracture connections. Temperature logs have been taken during pressurization, production, and thermal recovery periods and have been able to locate fractures and porous zones /39/. Temperature surveys made in hole GT-2B during shut-in and at different times during a subsequent flow test are summarized in Figure 5.18. The temperature profile during shut-in shows the effects of residual heating from a previous flow test at the locations marked 1, 2 and 3. Heat transfer calculations based upon the flow test measurements indicate that the main connection is at location 2, whilst the secondary connection is at 1, and the tertiary (and quite minor) connection is at 3. The LASL temperature probe is quite accurate. It has been calibrated to have an error or no more than 0.26°C and a resolution of 0.01°C , which is considerably better than that ascribed to thermistor probes in Reference 42.

5.4.2 Flow Meter Logs

A number of flow meters, each employing a different operating principle, are available for measuring the velocity of internal flows such as is found in process piping /43/. Only one type of flow meter currently

Figure 5.17. Temperature log, computer-derived differential temperature log and caliper log of Borehole CH-3 at Raft River Geothermal Reservoir /41/.

Figure 5.18. GT-2B temperature surveys during shut-in (background survey) showing residual heating from previous flow tests and at increasing times during subsequent flow test. The main flow connection is at position 2 with subsidiary connection at 1 and 3 /25/.

exists for borehole use, and that is the spinner type /42/. A spinner flow meter contains an impeller or turbine rotor that spins at a rate proportional to the velocity of fluid flowing through the meter. At low velocities near the minimum detection threshold, some nonlinearity will be present in the response because of bearing friction. The minimum flow velocity that will turn the impeller is about 0.4 ft/s. This threshold sensitivity is about the same for commercial tools /44/ and a Well Worth tool modified by LASL /24/. Low volume flow rates in large boreholes can be measured by decreasing the flow area, either by packers or with a nozzle, e.g., LASL has reported measuring a flow of $0.017 \text{ ft}^3/\text{s}$ near the bottom of hole GT-2B at Fenton Hill. By way of comparison, this flow is about three-quarters of what can be supplied by a household faucet. Schlumberger rates its spinner at 260°C ; LASL rates its tool at 200°C . An example of the usefulness of a spinner for logging flow entries is illustrated in Figure 5.19.

Figure 5.19. Reported results of a LASL-built spinner survey tool run in hole GT-2B showing the major flow entry regions as steps of decreasing total flow as the tool is lowered down past each major flow entry /24/.

5.4.3 Tracer Logs

Tracers are particularly useful in steady flow situations where they effectively tag individual fluid particles whose subsequent motion can then be studied as a function of time and position. Intricate flow paths can be discerned and transit times measured. Tracers are indeed a powerful diagnostic tool. The most common tracer logs make use of radioactive materials such as I^{131} or Br^{82} , which have a half-life of 8 days and 35.5 hours, respectively, and can be detected by conventional gamma-ray logging tools. An isotope such as tritium is not as useful for borehole logging as either I^{131} or Br^{82} , because its 12.1 year half-life would result in the contamination of subsequent surveys. In addition to radioactive tracers, sodium fluorescein dye has also been used at Fenton Hill. A dye requires down-hole sampling and laboratory analyses. It is believed that a radioactive tracer is a superior diagnostic tool. Radioactive tracers can be used to identify flow entries into a well as indicated in Figure 5.20. The entries are sharply defined when the tracer first appears, but diffusion and transport smear the record at late times. Transport also causes the gamma pulse to move up the well so that only the onset of a gamma pulse gives an accurate location for the inter-well connection. Flow exits out of a well can also be identified from the residual radioactivity of tracers adsorbed onto the fracture surface.

Figure 5.20. Tracer log showing the sequential appearance of Br^{82} at several well interconnections. LASL experiment in hole GT-2B at Fenton Hill /45/.

SECTION 6

RESERVOIR FRACTURE STRUCTURE BASED ON CONVENTIONAL BOREHOLE LOGS

Test borings at Fenton Hill and several surface exposures of the basement rock in New Mexico lead to the view that the rock in the Fenton Hill reservoir is not a recent monolithic intrusion of granite, but rather is an igneous metamorphic rock that evolved over millions of years and underwent several periods of deformation and igneous rock injection /25,46/. It follows that the hot dry rock reservoir is likely to have a complex structure that may influence not only the interpretation of data used to map the fractures which form the heat transfer surfaces between wellbores, but also the formation of the hydraulically induced fractures themselves. Thus, for the purpose of evaluating techniques for mapping fractures and for testing the consistency of measurements, it is useful to have a detailed structural model of the geothermal reservoir. The development and applications of such a model along with certain unresolved matters are described in this section. Conventional borehole logs were sufficient to provide data for inferring the dip, strike, number, spacing, and size of fractures and other weakness planes which intersect the borehole. It is assumed that the fractures and dikes which intersect the borehole are not simply local phenomena, but are representative of the rock structure at some distance from the wellbore. As it now stands, most conventional logs are not adequate for determining the lateral extent of fracturing. As a first approximation, the intercepts at the borehole are mapped into the far-field using a planar geometry for fractures and dikes. Details of the model are presented in Subsection 6.1. Results concerning fracture roughness and fracture frequency--the initial reason for developing the model--are given in Subsection 6.2. Certain questions have not been completely answered, especially those concerning (i) the geometry of seismic zones located at some distance from the wellbore, (ii) the direction of permeable fractures, and (iii) the extent of hydraulically induced fractures. These topics are discussed in Subsection 6.3.

6.1 RESERVOIR FRACTURE MODEL

Fractures and other weakness planes, inferred from logging data, were categorized as types 1 through 5 on the basis of their size estimated primarily by crosscorrelating caliper, electric, and acoustic logs, and by making use of some supplementary data from gamma ray, silicon/calcium, density, and drilling-related logs.

6.1.1 Fracture Size

It was assumed that when the larger erosion zones (caliper deflections) coincide with the regions of greatest fluid penetration (resistivity deflections) and greatest acoustic attenuation (zones of low velocity), the major fractures of type 1 have been identified. Similarly, when small breaks occurring in smooth portions of the borehole correspond with small indications of fluid penetration and with minor perturbations or disruptions of the acoustic records, type 5 or very minor fractures are identified. Types 2 and 4 are intermediate categories of fracture deformation. Type 3 is less specific. It refers to significant borehole erosion identified in the caliper log associated with rock contacts, usually dikes.

The size associated with each type of fracture is indicated in Table 6.1. The magnitudes of the differential slip are, in fact, not known from measurements, but rather are estimates based upon experience with underground mapping in hard rock in the western United States. For example, type 1 displacements have been set equal to those of large fractures which might possibly extend a few kilometers. Types 2 and 4 are associated with progressively smaller and shorter fractures. Type 3 are assumed equivalent to type 2 fractures in terms of offsets and width because they are permeable weaknesses of considerable extent. Because of the cementitious nature of injected dikes filling in weakness voids, they are not considered equivalent to type 1. The type 5 weaknesses are thought to represent cracks with a limited length of perhaps a few tens of meters.

Table 6.1. Characterization of fracture type based upon subjective analyses of Fenton Hill logs below 5800 feet. Differential slip and opening dimensions are assumed; frequency is determined from Figure 6.1 and Table 6.3.

Relative Weakness Type	Symbol	Estimated Magnitude		Average Spacing Between Fractures (m)
		Differential Slip (m)	Fracture Opening, Max. (mm)	
1		$10^{-1} - 1.0$	3	40
2		$10^{-2} - 10^{-1}$	0.5	10 - 13
3	Altered Zones Dike Injection		0.5	10 - 40
4		$10^{-3} - 10^{-2}$	0.05	4 - 7
5	Not Shown	$0 - 10^{-3}$	0.005	1.3

6.1.2 Fracture Orientation

In principle, the directions of a planar weakness--the dip and strike--can be determined from borehole logs. In practice, this can be a difficult task, and the results will be quite uncertain if the logging runs were not designed to yield the necessary data. Such is the case with some of the Fenton Hill data obtained with commercial tools. Fortunately, several logging runs were made with tools that did allow the dip and strike to be measured and the error associated with the measurements to be estimated. A considerable amount of the data in our possession were obtained with commercial two-independent-arm calipers which cannot establish the dip of a weakness plane with any certainty. What can be obtained from the commercial caliper log is a rough indication of whether a fracture intersects a borehole in a low or steep angle. An indication of a low dip can be quite unreliable because it is entirely possible

for a steeply dipping fracture to give the appearance of a horizontal fracture to a device that makes only two independent measurements. The best that can be done with a two-independent-arm caliper is to assume that if enough measurements are made, then a high percentage of indicated shallow dips will, in fact, arise from near-horizontal fractures. An indication of a steep angle, on the other hand, can only arise from a steeply dipping fracture. As it turned out, the two-independent-arm caliper registered a large number of steep dips with about an equal number of dips having apparently opposite sign. Because the tool did not contain an orientation measuring device, it cannot be stated with certainty that fractures did actually crisscross. We merely assume this to be the case rather than being an artifact of tool rotation, which has been measured to be small effect with an oriented diplog. To actually set the value of the angle associated with the steep dips, recourse had to be made to other measurements.

Based on measurements employing six different techniques, the dip of fractures has been inferred to vary from 66 degrees to near-vertical, Table 6.2. A seventh technique employing gamma ray detection determined the dip of the granite/gneiss contact surface to be 63 degrees, which suggests that the reservoir has a structural weakness with a dip of approximately 63 degrees. For the intended purpose of the fracture structure model, a dip angle of ± 70 (± 10) degrees is considered to be sufficiently accurate. An additional feature of the weakness plane structure is a set of shallow angle dip planes which are inferred from the two-independent-arm caliper measurements. The three sets of weaknesses crisscross to produce a reservoir that is both fractured and penetrated by dike-like intrusions, as shown schematically in Figure 6.1.

The applications for which the structural weakness model was developed required no knowledge of fracture strike. In actual practice, the determination of strike is crucial for the placement of boreholes. Measurements indicate two general trends for fracture strike: one to the northwest and the other to the northeast, as indicated in Table 6.2. The experimental results indicate a fair uncertainty in the value of the strike angle at essentially the same locations. It appears that there are no basic physical

Figure 6.1. Schematic vertical section illustrating fracture and weakness structure inferred from single borehole geophysical log data below 5800 feet at Fenton Hill.

reasons why a televiewer, an impression packer, and a three-arm-caliper should not yield accurate determinations of the strike. Experimental uncertainties are discussed in Subsection 5.2, while matters concerning the two different strikes are discussed in Subsection 6.3.2.

Table 6.2. Fracture orientations at the borehole. Referenced data reports do not consistently distinguish between true North and magnetic North (a difference of approximately 17 degrees).

Hole	Depth	Dip (deg)	Strike	Tool	Comment	Reference
EE-1	6438	~ 90	N70°W	Impression Packer	Suspect by LASL	35
	6449	~ 90	N70°W	Impression Packer	Suspect by LASL	35
	6530		N25°E	Impression Packer		39
	6533		N3°E	Televiewer	Suspect by USGS	28
	6560		N25°E	Impression Packer		39
	6562		N12°E	Televiewer	Suspect by USGS	28
	9650		N53°W	Temperature & Tracer	Dip Assumed Vertical	35
	9670	80	N70°W	Televiewer	Cross Fracture	25
	9670	90	N20°E	Televiewer	Cross Fracture	25
GT-2	8640	71	N27°W	Televiewer		25
GT-2B	5840	75		4-Arm Diplog		
	8852	66	N18°E	3-Arm Caliper	True North	24

6.1.3 Measured Fracture Distribution

The data supporting the fracture distribution model are listed in Table 6.3. These were compiled while doing the crosscorrelation of the principal geophysical logs of holes GT-2, GT-2B, and EE-1. Data between the intervals of 5800 feet to 9400 feet in the three holes were tabulated by apparent fracture and

Table 6.3. Frequency of fracture and weakness plane intercepts with vertical boreholes at the Fenton Hill hot dry rock reservoir as a function of fracture size. Fracture size (type) defined in Table 6.1.

- (a) Number of intercepts per 100 ft interval in three different holes inferred from several different types of logs. Hole GT-2: two-independent-arm caliper and four-arm diplog used from 5800 to 6600 ft; caliper only below 6600 ft. Hole GT-2B: VDL acoustic and laterolog used from 6000 to 8800 ft. Hole EE-1: Two-independent-arm caliper from 6500 to 9500 ft.

Depth Intervals (ft)	Hole GT-2				Hole GT-2B				Hole EE-1			
	Fracture Type											
	1	2	3	4	1	2	3	4	1	2	3	4
5800 - 5900	0	2	0	6								
5900 - 6000	0	1	1	3								
6000 - 6100	1	1	3	4	2	1	0	3				
6100 - 6200	0	0	0	5	1	2	0	3				
6200 - 6300	0	2	1	10	0	0	0	4				
6300 - 6400	0	2	0	7	0	0	0	4				
6400 - 6500	0	0	0	8	0	1	0	4				
6500 - 6600	0	3	3	8	2	2	2	4	0	1	0	4
6600 - 6700	0	1	0	6	2	2	2	4	0	0	0	2
6700 - 6800	1	1	1	4	2	2	2	4	0	0	0	2
6800 - 6900	1	0	1	7	2	2	2	4	2	0	1	4
6900 - 7000	0	0	0	2	2	2	2	4	0	0	0	4
7000 - 7100	1	1	1	3	2	2	2	4	0	1	0	3
7100 - 7200	0	1	0	2	2	2	2	4	1	0	1	3
7200 - 7300	0	1	1	3	2	2	2	4	0	0	0	4
7300 - 7400	0	0	1	0	2	2	2	4	0	0	0	3
7400 - 7500	0	0	0	3	2	2	2	4	0	0	0	1
7500 - 7600	0	0	0	3	1	1	1	4	0	0	0	2
7600 - 7700	0	1	0	1	0	1	0	4	0	0	0	4
7700 - 7800	0	0	0	3	0	0	0	2	1	0	0	3
7800 - 7900	0	0	0	2	0	0	0	0	0	0	0	2
7900 - 8000	0	0	0	3	0	1	0	4	0	1	0	1
8000 - 8100	1	0	0	3	0	0	2	1	0	0	2	4
8100 - 8200	0	0	0	2	0	0	0	5	0	2	2	2
8200 - 8300	0	0	0	4	1	0	2	5	0	0	0	0
8300 - 8400	1	1	1	2	0	0	1	7	0	1	0	2
8400 - 8500	0	0	0	1	0	4	0	1	0	0	0	3
8500 - 8600	0	0	0	2	0	2	0	4	0	0	0	5
8600 - 8700	0	0	0	2	0	0	1	5	0	1	0	5
8700 - 8800	0	0	0	0	0	3	2	5	0	1	1	3
8800 - 8900	0	1	0	6					0	1	0	7
8900 - 9000	0	0	0	4					0	1	2	3
9000 - 9100	0	1	2	3					1	1	1	3
9100 - 9200	0	1	1	2					0	1	0	8
9200 - 9300	0	0	0	1					0	1	2	2
9300 - 9400	0	0	1	2					0	0	2	2
9400 - 9500	1	1	0	2					0	2	1	3

- (b) Average intercept frequency per 100 ft interval with logging tools as a parameter.

Tools	Fracture Type				Comment
	1	2	3	4	
Caliper & Diplog	0.13	1.4	1.0	6.4	GT-2 5800 - 6000 ft
Caliper	0.21	0.38	0.34	2.7	GT-2
	0.17	0.50	0.50	3.0	EE-1
VDL & Laterolog	0.25	1.2	1.0	3.75	GT-2B

weakness type over 100-foot depth intervals. The methods used to estimate fracture existence and location are described in Section 5. The tabulated results not only reveal some interesting and important features of the fracture pattern, but also provide an indication of the sensitivity of different tools to fractures. On the average, very large fractures (type 1) intersect a near-vertical borehole only infrequently--about once every 400 to 500 feet. The wide spacing arises in part because the fractures themselves are nearly vertical. The normal distance between fracture planes is much less than the borehole intersection distance, being reduced by the secant of the dip angle to about 170 feet. The fracture-borehole intersections become more frequent as the size of the fracture is reduced, e.g., for a type 4 fracture the intersection distance is approximately 32 feet, while the spacing between fractures is about 11 feet. The variability arising from the subjective method of picking fractures is less between different boreholes using the same tool than it is in essentially the same borehole using different tools. For example, the average number of fractures and weakness planes inferred from a two-independent-arm caliper varies by less than 20 percent between the GT-2 and EE-1 boreholes at Fenton Hill, while the averages vary by 40 to 140 percent in GT-2 and GT-2B when both VDL acoustic and Laterologs are used instead of a caliper. This result implies that the weakness structure is rather uniform at Fenton Hill, but that the criteria used to pick fractures with the deeper sensing tools are not in concert with that used with the caliper log.

6.2 FRACTURE ROUGHNESS AND FRACTURE FREQUENCY

If a hot dry rock reservoir were a monolithic block of granite penetrated by only a few nonintersecting fractures, then certain problems regarding fracture mapping could be resolved quite simply. For example, the origin of backscattered electromagnetic or acoustic energy could only be a fracture heat transfer surface. Multiple scattering and multiple mode conversion between P- and S-waves would not exist. For almost all wavelengths of practical interest, reflections would be specular. The evidence presented in Subsection 6.1 indicates that the Fenton Hill reservoir is highly fractured, and consequently rather complicated wave interaction

phenomena may be expected. A fundamental question that arises when probing for fracture planes with either electromagnetic or acoustic waves is whether reflections are specular or diffuse. The model developed in Subsection 6.1 can be used to answer this question by establishing the roughness of a major fracture plane, i.e., a type 1 fracture. The surface roughness of a fracture is caused by offsets arising from slip along the other weakness planes which intersect the fracture in question. The distance between fracture intersections, indicated schematically in Figure 6.1, varies between 2 and 55 meters along a type 1 fracture. The slip offsets and the spacing between offsets are listed in Table 6.4. The effective roughness height is reduced from the slip offset by the sine of the intersection angle (Figure 6.1) which is approximately 0.75 for the Fenton Hill geology. When searching for a major fracture plane with electromagnetic or acoustic energy, waves will be reflected back to the receiver by the numerous minor fractures which crisscross the reservoir. To estimate the amount of noise or clutter produced as a ray traverses minor fractures, it is useful to know the number of reflecting planes or fractures that intersect the ray. To simplify matters, we have eliminated the angular dependence by averaging over a large number of angles. The average spacing between fractures along a hypothetical average ray probing outward from a vertical borehole varies between 1.3 and 40 meters, depending upon the type of weakness as indicated in Table 6.4.

Table 6.4. Fracture plane offsets and spacings

Weakness Type	Differential Slip (m)	Average Spacing Between Fractures (m)	Spacing on Main Fracture (m)
1	10^{-1} - 1.0	40	55
2	10^{-2} - 10^{-1}	10 - 13	20
3	10^{-2} - 10^{-1}	10 - 40	40
4	10^{-3} - 10^{-2}	4 - 7	8
5	0 - 10^{-3}	1.3	2

6.3 UNRESOLVED ISSUES

The fracture structure model derived from conventional borehole logs (Subsection 6.1), does not address the question of how far fractures extend from the borehole. Indeed, most conventional borehole logs measure reservoir properties within less than a meter of the borehole and, consequently, are incapable of yielding information on the lateral extent of either natural or hydraulically-induced fractures. In this section, we discuss certain problems concerning fracture structure that cannot be resolved by use of conventional borehole logs, and also introduce some information based on techniques still under development in an attempt to clarify the status of fracture mapping research.

6.3.1 Geometry of Seismic Zones

Passive acoustic measurements have been interpreted in two different ways by workers at LASL to yield two different loci of seismic activity, i.e., the same data have been reduced to give two different directions for the region of seismic activity /25/. This apparent paradox has not been resolved. Moreover, two different models have been used to explain the observations, resulting in alternate directions for the main fracture plane. At the one depth where the two different methods can be compared, two of three alternate solutions give the same general trend for the strike of the main fracture, i.e., northwest. The LASL shear model fits in with the picture of multiple fracturing developed in Subsection 6.1, i.e., crosscutting fractures can connect the wellbore with a distant massive fracture. Slippage along the crosscutting fractures are thought to be responsible for the seismic activity. Additional measurements with multiple geophone locations have been recognized as necessary to resolve the validity of each model /25/.

6.3.2 Direction of Permeable Zones

The LASL model of seismicity implies that slippage can occur along planes trending to the northeast. From other investigations of seismic activity following fluid injection into fractured prestressed regions, it appears likely that fluid will migrate along the most permeable paths, and when the paths intersect regions of critical stress balance, the fluid pressure will trigger microseisms /47/. Continued injection should then produce microseisms

at increasingly distant locations. Borehole measurements have confirmed the existence of fractures striking to the northeast. Attempts to relate the direction of permeable fractures within the Fenton Hill reservoir to either current or ancient stress fields outside of the Fenton Hill caldera almost certainly rest on tenuous ground. Nonetheless, it is interesting to note that basement outcrops near Albuquerque indicate an old fracture pattern trending northeast /48/, while a recent determination of in situ stresses near Socorro suggest a fracture pattern trending northwest. These observations are in qualitative agreement with the current view that major hydraulic fractures trend northwest, while subsidiary leakage paths trend northeast.

6.3.3 Extent of Hydraulic Fracturing

It is thought that major weaknesses, when oriented to in situ stresses so that tensile openings can occur, will inflate first to become the major initial hydraulic fractures. Even if packers were used to force the hydraulic fracture to originate in a naturally unfractured section, it seems likely that a fracture would develop only a short distance before intercepting a favorably oriented natural weakness, which would then take over as the major hydraulic fracture path. Other weaknesses would also intersect the major initial hydraulic fracture path creating crossconnections to other favorably oriented weaknesses roughly perpendicular to the minimum horizontal component of in situ stress.

At the present time, three types of logs have been tested for their ability to define the extent of fracturing away from the borehole. One is a conventional technique: the induced potential. The other two are not normally used in commercial practice, but show promise of being useful; namely, passive microseismic detection and borehole-to-borehole acoustic transmission. One test of the induced potential method demonstrated that a fluid-filled fractured region gives rise to a measurable potential variation. Thus, the extent of fracturing parallel to the borehole can conceivably be related to the potential distribution, but the necessary analysis and confirming experiments have apparently not been performed. The microseismic technique has been used to provide fracture maps, but the validity of

alternate interpretations needs to be settled. The active acoustic method is made complicated by the strong interactions and mode conversions that occur when acoustic waves traverse a fractured region. Cutting off shear wave propagation by fracture inflation has been shown by experiment to be a powerful method for mapping fractured regions. The limits of resolution of acoustics for mapping fractures needs to be determined, i.e., can acoustics map large discrete fractures within a region containing many fractures or can only the boundaries of the region be mapped?

SECTION 7

CONVENTIONAL LOG SUMMARY

With extant borehole logging techniques, it is possible to crosscorrelate a set of conventional logs to infer the location and orientation of fractures where they intersect a borehole. The usefulness of conventional tools is diminished, however, by two principal factors: temperature limitations and uncertain interpretations of the data. The situation can be improved by (1) upgrading the temperature capabilities of tools, (2) calibrating tools in a hard rock of known fracture structure, (3) developing models of tool operation in a fractured medium appropriate for hot dry rock operations, and (4) requiring greater attention to logging details in the field.

Logs obtained during drilling should, in principle, assist in inferring subsurface fracture conditions, but during operations at Fenton Hill, only core recovery provided substantial data. Based upon experimental evidence, six logs, when used synergistically, appear useful for mapping the intercepts of natural fractures with a borehole once drilling has ceased. They are the (1) caliper, (2) resistivity dipmeter, (3) televIEWer (acoustic imaging), (4) television, (5) impression packer, and (6) acoustic transmission. The dipmeter and acoustic transmission methods require improved analyses, while all six would benefit from improved high temperature capabilities. A seventh technique, the silicon/calcium log, is useful for differentiating between fractures and zones of chemical alteration, but is in itself not capable of detecting fractures. Six other techniques appear to be of marginal value for locating natural fractures at the present state-of-the-art. They are the (1) density log, (2) spontaneous potential log, (3) resistivity methods that sample large volumes of rock, (4) gamma-ray log, (5) spectralog, and (6) temperature log. The density log has shown spurious responses thought to arise from tool tilt. Problems with cross-correlating a density log with a caliper log have raised questions about inferring fracture porosity from a formation density compensated log. The density log, in our opinion, requires

testing and calibration in a granitic medium with a known fracture structure. A differential temperature measurement might conceivably record temperature changes arising from fluid seepage at natural fractures, but the technique has not been tested in a hot dry rock reservoir. Temperature logs appear to have their main use in mapping hydraulic fractures under forced flow conditions.

After hydraulic fractures have been produced, the techniques that work for mapping natural fractures can again be employed. In addition, temperature, flow meter, and tracer techniques can be used to determine the size of fractures. Well interconnections can also be located with the latter three methods. An uncertainty in tool depth that is apparent when correlating different logs can be prevented in future runs by installing a special fiducial collar and by keeping more detailed logging records.

The conventional logs have been used to develop a model of the fracture structure of the Fenton Hill reservoir, and this model shows the reservoir to be crisscrossed by a large number of natural fractures and dikes. The accuracy of the model rests on the validity of extrapolating near-wellbore data to the far-field and can be tested only by obtaining far-field data with new techniques. By serving as a first approximation, the model has been helpful for designing advanced mapping methods.

SECTION 8

FRACTURE MAPPING ACTIVITIES IN THE UNITED STATES, CANADA AND SWEDEN

The use of radar and conventional logging techniques to map fractures from a geothermal wellbore has been dealt with in this report either from first principles or from the analysis of experimental data. To ensure that we have not taken a parochial view of fracture mapping operations, we have reviewed other fracture mapping activities in the United States, Canada, and Sweden via field trips, telephone conversations, technical reports, and journal articles. The results of the review are presented below. Although acoustics and signal processing techniques have been discussed with other organizations, the emphasis has been on radar and conventional logging techniques; the former two topics will be treated in more detail during the second phase of our work.

8.1 MAJOR PROGRAMS FOR MAPPING FRACTURES

Four major programs, in addition to the one sponsored by the Division of Geothermal Energy, are concerned with subterranean fracture mapping. To evaluate the suitability of a hard rock setting for a nuclear waste repository, both the Department of Energy, Office of Nuclear Waste Isolation, and Atomic Energy of Canada Limited are actively engaged in developing techniques for mapping fractures in granite. Methods for detecting fractures, voids and water-filled cavities are being investigated both by the Department of Transportation (Federal Highway Administration) and the Bureau of Mines. The former agency is interested in improving tunnel boring operations both from an economic and safety standpoint, while the latter agency is directing its efforts to improving the economic recovery of coal and the safety of mining operations.

Office of Nuclear Waste Isolation (ONWI) /49/. ONWI through its contractor, the Lawrence Berkeley Laboratory (LBL), and in cooperation with both the Swedish Nuclear Fuel Safety Board (KBS) and the Swedish Geologic Survey (SGV) has conducted a series of fracture mapping tests in a granitic setting at a depth of approximately 340 meters in an abandoned iron mine

at Stripa, Sweden /33,50-54/. Thirteen different types of measurements were made to investigate fracturing. LBL fielded nine tools: (1) gamma-ray, (2) formation density (uncompensated), (3) porosity (neutron), (4) caliper, (5) resistivity, (6) temperature, (7) intra-hole acoustic, (8) cross-hole acoustic, and (9) mechanical modulus. SGV fielded both normal and lateral electric logs, and a differential resistance log. In addition, use was made of core recovery and borehole television. LBL believes that the sonic waveform, caliper, and differential resistance tool were the most useful for locating fractures, but that all three tools need to be improved. The acoustic logs were displayed in a form similar to a VDL, and we believe that the comments of Section 5.2.6.4 also apply to the LBL tool. LBL mapped borehole-fracture intercepts by crosscorrelating signals from different tools in a manner similar to that done in the DGE program (Section 5.2). LBL observed that only a small fraction of the fractures logged from core or television produced a sonic waveform that indicated a fracture. The SGV differential resistance tool is quite different in construction from a resistivity diplog, but the action of the two tools is similar. Additional development work for the SGV tool is recommended by LBL--a recommendation similar to ours for the resistivity diplog. SGV believes that the application of electrical methods to crystalline rock is unsatisfactory for neither is the analysis well-developed nor are the tools designed for operation in a rock matrix of high resistivity ($\rho \approx 10^5 \Omega\text{-m}$), instead having been designed for use in sedimentary rock ($\rho \leq 10^3 \Omega\text{-m}$). To wit, the low frequency electrical properties of crystalline rock are governed by pore space and fracture characteristics that depend heavily on the fracture pattern and conducting material within the fracture, but in a manner that is incompletely understood.

The operating principles of twelve of the tools used at Stripa are similar to those discussed in Section 5, although the implementation of the techniques was in some cases different. One tool used at Stripa but not at Fenton Hill was a Colorado School of Mines Young's modulus cell. Although a decrease in modulus correlated with an increase in fracturing,

the tool was not used extensively because the region of rock sensed by the cell was quite small. Other techniques can map borehole fracture intercepts in a more expeditious manner. LBL used a signal thermistor to make temperature measurements. The comments of Section 5.4.1 regarding differential temperature measurements also apply to the LBL experiments as do the comments of Section 5.2.1 concerning the use of a single trace caliper by LBL.

Atomic Energy of Canada Limited (AECL) /55/. AECL, working principally with Energy, Mines, and Resources Canada and the Geological Survey of Canada, is engaged in a program of airborne, ground, and borehole measurements to (1) determine the size and shape of rock masses that might be suitable for a nuclear waste repository, and (2) map and characterize fractures within the rock masses /56/. Before reviewing the borehole measurements, we mention one surface technique examined by AECL. Using powerful navy transmitters operating in the 15 to 25 kHz (VLF) band as a source of electromagnetic radiation, measurements were made of the magnetic field induced at the ground surface by subterranean return currents. It is hypothesized that the underground currents are channeled by conductive fractures; hence, the location and size of fractures are inferred from the magnitude and phase of the components of the magnetic field vector. The depth of investigation is limited by the skin depth with both the incident and secondary waves each being attenuated by ground loss. For example, at $f = 10^4$ Hz with $\sigma = 10^{-4}$ S/m, the skin depth is 503 meters. Whether satisfactory operation could be achieved at $f < 10^2$ Hz where $\delta = 5030$ meters has apparently not been investigated.

The borehole measurements include seismics, radar, and temperature. Additional techniques under study include gamma-ray, radioactive tracers, and borehole acoustics. The seismic studies uncovered large variations in P-wave velocity, but these variations often did not correlate with the borehole geology determined from core samples /57/. It was suggested in Reference 57 that the seismic survey was influenced by a volume of rock with a radius of 8 to 15 meters surrounding the borehole, i.e., substantial

variations in rock properties at some distance from the borehole influence the received signals. The seismic data were also interpreted to yield borehole-fracture intercepts from the arrival times of tube waves /58/. It was suggested in Reference 58 that inasmuch as tube waves arise from the squeezing effect of compression waves on fractures that intersect a borehole, it might be possible to relate the size of the fracture to the tube wave signature. The seismic data were further interpreted on the basis of the theory of seismic velocities in cracked solids to yield the density of (small) cracks surrounding a borehole /59/. Because the attenuation of seismic signals is believed to be caused principally by fluid flow between cracks, the possibility was raised of estimating rock permeability by using seismic techniques. For the geothermal reservoir program, we note that the relative magnitude of the effects on seismic signals arising from a few very large fractures and from numerous small-scale cracks must be quantified.

By emplacing a 100-MHz radar system in boreholes spaced 10 and 46 meters apart in a low magnetic susceptibility granodiorite, it was determined that a one-way range of at least 46 meters could be achieved in the transmission mode /60/. If accurate performance figures for the radar were available, the backscatter range could be calculated.* The best that can be said based on available data is that the backscatter range is less than 23 meters, which is about one-half that determined from Figure 2.3. Reflections recorded with the transmitter and receiver in the same borehole were interpreted to arise from fractures. By extrapolating the received signal to zero time, the borehole-fracture intercepts were determined and found to be in good agreement with those inferred from television, density, resistivity, and gamma-ray logs.

* It can be shown that the backscatter range, R_2 , for a large diffusely scattering fracture plane is related to the one-way transmission range, R_1 , by $R_2/R_1 = (\lambda/8 R_1)^{1/3} \exp(\alpha R_1 (1 - 2 R_2/R_1)/3)$. If the range were controlled solely by dissipation in a lossy medium, then the backscatter range would be one-half the one-way transmission range. In general, the backscatter range will be less than one-half the one-way transmission range because of scattering effects.

Federal Highway Administration (FHWA) /61/. The FHWA has emphasized hardware, field demonstrations, and data manipulation. Data interpretation is recognized to be a crucial aspect of the detection problem, although it has not yet been possible to give it adequate attention. The basic idea behind the agency's work is that rock quality ought to be determinable by deploying a small diameter geotechnical sensing tool within a long, horizontal, air-filled borehole instead of employing the established and expensive practice of driving an exploratory inspection tunnel. Operation with single and multiple boreholes has been considered; the latter is more expensive than the former, but is more versatile for it allows transmission measurements to be made. Attenuation has focused on placing radar, acoustic and resistivity instruments within the tool. Radar and acoustics are complementary techniques in that both should detect voids and fractures, but should respond differently to anomalies. Resistivity was selected for a less fundamental reason; namely, the large extant data base.

The basic operating principles of the tools are the same in the tunneling and geothermal business, but certain aspects of the design are different, mainly, because in tunneling the borehole is air-filled, while in geothermal mapping the wellbore is water-filled under normal circumstances. The acoustic instruments must employ pads pressed against the borehole wall to couple energy into the rock. If the acoustic design is somewhat more complicated in the tunneling project, then the radar design is a bit simpler inasmuch as a lossy water medium does not surround the antenna. The resistivity measurements are made with a magnetic induction technique to obviate the need for contact between the tool and borehole wall. Four field experiments using various techniques were carried-out, but in only one was a mine-back possible. Excavation verified a tomographic VHF electromagnetic map of grout injection into a sand pit, but at a construction site where mine-back was not possible, an anomaly mapped by VHF tomography was unseen by acoustics. Radar equipment is being readied for a test in a tunnel pilot boring operation.

Bureau of Mines /62/. The Bureau of Mines, Denver, has employed pulsed surface radars with a center frequency of 30 MHz. The radar data have been interpreted to indicate the occurrence of more fractures than are indicated by, say, resistivity measurements. Furthermore, it is believed that echoes from fractures arise from a change in material properties across the interface, quite unlike the model used in Subsection 2.5.1 to describe a geothermal reservoir. The Bureau of Mines model has not been verified by mine-back. Attempts to delineate anomalies (cavities and weak zones) have been hampered by the omni-directional properties of antennas. The main effort until recently has been the production of clean, well-damped pulses. The Bureau of Standards is currently developing a directional surface antenna for the Bureau of Mines. Bureau of Mines personnel believe that their efforts have not yet yielded practical tools. As is the case with most users of radar data, they feel that data interpretation is the biggest unresolved problem.

8.2 OTHER FRACTURE MAPPING ACTIVITIES

The analysis of subterranean radar data has until recently usually focused on picking reflections from individual traces of received signal amplitude vs. time. The received echoes are seldom replicas of the transmitted pulse, but rather are modified by a number of effects which include dispersion by the medium and interference from separate multiple reflectors or from different parts of a large reflector. The origin of the reflections is often unknown, and it is difficult to distinguish between clutter and an echo that has arisen from the object of the radar mapping, e.g., a material interface or a fracture. Various assumptions and hypotheses often find their way into the data reduction process. Verification of fracture geometry, either via mining or drilling, is seldom attempted, except in adequately funded programs. Signature analysis is a subject which is receiving increased attention. At the present time, we are unaware of a workable inverse scheme for target identification. For the near future, at least, we believe that for applications within a geothermal reservoir, the use of a conducting fluid to map fractures that intersect the borehole is the most

promising radar detection and identification technique. Examples of data and the difficulties experienced in their interpretation can be found in References 1, 2, 4 and 63-67. Precise of these references pertinent to the geothermal program are set forth below as are some recent developments obtained via telephone conversations and field trips.

Holser, et al., /1/ experienced considerable difficulty in determining the geometry of the boundaries of a salt dome because of the lack of azimuthal directivity from a borehole antenna. Data from other geophysical logs were necessary to form a consistent picture of the location of the flank of the salt dome. The reflecting surfaces themselves did not produce a signal which correlated for any appreciable distance along the borehole traverse; in fact, correlations extended only over a region comparable to the beam width. Stewart and Unterberger /2/, using a narrow beam produced by a large antenna stationed within a salt mine, observed numerous reflections originating from within the salt, but the nature of the reflectors was unknown. Moffatt and Puskar /4/, employing surface radars to look below the surface of a quarry, observed large increases in echo amplitude under rain soaked conditions compared to dry conditions, presumably arising from water-filled fractures. Confirmation of the existence of a radar-mapped fault was foiled by extensive fracturing during subsequent quarrying operations.

Ensco, Inc., /63-66/ has displayed radar returns, not only as individual traces, but has also investigated the use of record sections, common depth point reflection techniques, and signal stacking. Additional signal processing, such as the migration schemes used in reducing seismic reflection data, might improve the quality of the radar displays. The use of record sections to aid the detection of fractures in a quarry using borehole radar indicated that at the present time the delineation of the exact configuration of a reflector is a very difficult task. Ensco has found that an impedance match cannot be obtained between a radar antenna with fixed characteristics and the ground over an appreciable length of borehole, a problem they attribute to seemingly random changes in the

impedance of in situ geologic materials. To overcome this problem, they are working on a tunable antenna. To alleviate problems associated with the propagation of pulses in dispersive, lossy media, they are investigating the use of synthetic pulse forming, i.e., forming a pulse from a large number of essentially continuous sine waves. A 600 MHz, 3-inch diameter borehole antenna with directional properties is also currently under development.

Southwest Research Institute /67-69/ has been involved with the design and fielding of three types of VHF radars: surface backscatter, subsurface borehole backscatter, and subsurface borehole-to-borehole transmission, and one type of CW FM UHF radar: high resolution, limited range (~ 1 foot) subsurface backscatter. The surface radar was used principally to detect tunnels and buried objects. The subsurface VHF radar is potentially useful to the geothermal fracture mapping program and was employed in the following ways: Anomalous regions, perhaps faults and sand channels, were detected within a radius of approximately 17 meters from a borehole passing through sedimentary rock and coal. Signals interpreted to arise from near-surface jointing and broken gneiss and schist were detected near the Forest Glen Metro station in Washington, D.C., but a planned mine-back to verify the interpretations was never performed. Near-surface tunnel detection was carried out by borehole-to-borehole transmission. The UHF radar was designed to measure the thickness of coal surrounding a tunnel during mining operations. In those cases where the interface between the coal and shale was sharp, the resolution was of the order of $\pm 1/4$ inch, but when the interface was diffuse, it could not be detected. A similar unit might be able to detect fracture intersections with a geothermal wellbore, but several conventional logging tools can already perform this task (Section 5). Like Ensco, Southwest Research is also developing a 3-inch diameter directional VHF antenna. Although not a pencil beam by any means, the antenna should be good enough to resolve the quadrant from which a signal originated. In most cases, an 8 to 10 nsec, unipolar, VHF video pulse (30 to 300 MHz) is used to excite their antennas. A monocyclic pulse, which has the advantage of a narrower spectrum than a half-cycle pulse (there is no DC component), has been used in some cases to improve

resolution, but perhaps with some decrease in range. Southwest Research's main efforts have been directed towards instrumentation development with only a subsidiary amount of labor expended on analyses. Data interpretation has usually been based on a pulse-echo time analysis. SWRI personnel believe that radar interpretations must be corroborated by other measurements, such as acoustics.

Sandia Laboratories is involved in the mapping of hydraulic fractures for the enhanced gas recovery program, and has also participated in programs initiated by the petroleum industry /70/. Three main techniques have been investigated: the measurement of the surface potential arising from passing a current between two well bores and the subsequent distortion of the potential field by current conducted along the hydraulically induced fracture, the measurement of seismic disturbances (Section 7.3.1), and the measurement of surface tilt (Appendix A). Although the potential method proved technically feasible in the Sandia application, the cost to implement it led to it being abandoned in favor of the other two techniques /71/.

SECTION 9

MAGNETIC BOREHOLE RANGING

The problems experienced while attempting to locate the GT-2 wellbore with respect to the EE-1 wellbore at Fenton Hill have led us to look for an alternate means of surveying wellbores. If a technique were available that could determine the position of one borehole, while it was being drilled, relative to an already completed borehole, then it might well be possible to increase the accuracy of drilling and to reduce the uncertainty in the determination of the separation distance between the completed boreholes. Based upon our experience with certain subterranean magnetic ranging techniques used to determine displacements resulting from large explosions /72/, and from the results of tests recently completed for the Bureau of Mines /73/, we examine the possibility of surveying wellbores in the Hot Dry Rock Program using magnetic techniques.

9.1 MAGNETIC RANGING AND ORIENTATION TECHNIQUES

The main idea of magnetic borehole ranging is that by placing a magnetic dipole of known source strength (a solenoid) in one borehole and by measuring the vector components and the phase of the a.c. magnetic field in a distant borehole, both the range and the orientation of one borehole with respect to another can be determined. Under what conditions this can be accomplished will be set forth in this section. Our main emphasis will be on determining the maximum distance for which magnetic ranging will work and what type of hardware is required.

The field of time invariant magnetic dipole expressed in terms of polar coordinates is

$$\vec{H} = \frac{m}{4\pi R^3} (\hat{i}_r 2 \cos \theta + \hat{i}_\theta \sin \theta) ,$$

where m is the dipole moment and θ is the angle between the z axis and the axis of the dipole. The field is measured in actual practice, however, in a Cartesian coordinate system fixed to an instrument package which, in general, is rotated with respect to the axis of the dipole. To locate

the solenoid in, say, borehole 1 from borehole 2 requires not only the determination of three rectangular coordinates, but also the two Euler angles specifying the rotation of the axis of borehole 1 with respect to borehole 2. Since the dipole moment of the solenoid is known, there are five unknowns to be determined from three vector measurements. Hence, several measurements at different locations must be made in borehole 2 to locate the solenoid in borehole 1. The problem is then overdetermined, and a data fitting process must be employed to reduce the data. Other than stating that the positions of buried magnets have been determined successfully using a magnetometer in a borehole /72/, we shall not go into the details of coordinate transformations and the accuracy of data fitting procedures. We shall instead treat the problem of data inversion accuracy in a parametric manner by performing borehole ranging calculations with different signal-to-noise ratios and by stating (without proof) that for signal-to-noise ratios of between 20 to 40 db the data inversion will be accurate to within at least a few percent.

9.2 MAXIMUM BOREHOLE SEPARATION

We now turn to estimating the maximum borehole separation that can be detected by magnetic ranging. To facilitate the analysis and to make the physical phenomena stand out, we simplify the mathematics by neglecting the effects of orientation and consider only the measurement of weak magnetic fields. Thus, we relate range, magnetic flux density, and magnetic moment by

$$R = \left(\frac{\mu_0 m}{4\pi B} \right)^{1/3} \quad (9.1)$$

The minimum useful B field is set by transducer noise and by magneto-telluric noise. The equivalent B field noise for three different magnetometers is listed in Table 9.1. By using a.c. excitation of the solenoid not only can the effects of both sources of noise be greatly reduced, but so can the contamination of the solenoid signal by the d.c. geomagnetic background. Since the magnetometer noise is broadband, the detected noise

level is decreased in direct proportion to the bandwidth. Thus, it is advantageous to use narrow band circuits; in the calculations we assumed $Q = 100$. Secondly, by using a.c. coupling the spatial variations of the geomagnetic field caused, say, by an irregular distribution of magnetite will not affect the data reduction process. Moreover, temporal variations in the geomagnetic field can, to a large degree, be filtered out. (The amount of field distortion at the signal frequency caused by patches of magnetite remains to be quantified.) At frequencies greater than about 1 Hz, magneto-telluric noise is dominated by atmospheric effects, i.e., lightning discharges. To estimate atmospheric noise, we use Maxwell's data for the mean value of the horizontal magnetic field noise density at the surface of the earth within a 1-Hz bandwidth during the summer in Boulder, Colorado /76/. Between 20 to 100 Hz, the spectrum is flat with a value of 117 db below 1 A/m. The noise density of the horizontal magnetic flux density is then $B_a = 1.77 \times 10^{-3} \gamma / \sqrt{\text{Hz}}$, where $\gamma = 10^{-9}$ tesla. This value, which is several db greater than measurements made at other locations by Maxwell and by other investigators, is a conservative estimate even when extrapolated (neglecting Schumann resonances) to 2.5 Hz (the lowest frequency that we have considered). We neglect the slight attenuation of the low frequency atmospheric noise with depth and calculate the total noise field from the rms value of the transducer noise and the low frequency atmospheric noise. A third advantage of using a.c. excitation is that it opens the possibility of using a magnetic loop to detect the B field instead of a magnetometer.

Table 9.1. Equivalent B field noise for magnetometers.
NOL is the Naval Ordnance Laboratory, and
JPL is the Jet Propulsion Laboratory.

Magnetometer	Type	Equivalent B Field Noise	Reference
Develco	Fluxgate	$3.3 \times 10^{-2} \gamma/\sqrt{\text{Hz}}$	74
NOL	Fluxgate	$3.10 \times 10^{-3} \gamma/\sqrt{\text{Hz}}$	75
JPL	Vector Optically Pumped Helium	$10^{-2} \gamma/\sqrt{\text{Hz}}$	76

The use of a.c. signalling is not without its complications. Because the field polarity reverses every half-cycle, a 180 degree ambiguity in the direction of the solenoid can be resolved only by measuring the instantaneous phase of the detected signal and comparing it with the phase of the solenoid excitation. When the magnetic field detector is moved to a new location in the borehole, the use of resonant circuits leads to a so-called "build-up time" during which the measurement approaches its steady state value. The build-up time constant is equal to $2/\Delta f$, where Δf denotes the bandwidth, so that the narrower the bandwidth the larger the build-up time. To make an accurate measurement, the settling or waiting time at each new location should be at least five time constants or $10/\Delta f$. For example, with $\Delta f = 0.025 \text{ Hz}$, the waiting time is about seven minutes. The excitation frequency cannot be made too high without introducing propagation effects into the analysis. Propagation modifies the static analysis with terms proportional to $2R/\delta$, when δ is the skin depth. For $\sigma = 10^{-4} \text{ S/m}$, which is a low frequency conductivity typical of wet granite, the skin depth is plotted as a function of frequency in Figure 9.1.

Figure 9.1. Skin depth vs. frequency. $\sigma = 10^{-4}$ S/m, $\sigma/\epsilon\omega \gg 10$. The magnetostatic analysis is accurate for $R \ll \delta$.

For a signalling range of approximately 300 meters, a frequency of 100 Hz will begin to introduce small modifications to the static results. At all frequencies of interest to magnetic borehole ranging, the ground acts as a good conductor, i.e., $\sigma/\epsilon\omega \gg 10$.

To continue, the maximum borehole separation for which the magnetic ranging technique will work is estimated from Equation 9.1. The minimum useful B field signal is set equal to either ten or one-hundred times the noise field to ensure that the signal strength is adequate to accurately invert the data. By parametrizing the signal-to-noise ratio, we also obtain a feel for how this quantity affects the range. The noise field for magnetometers is taken from Table 9.1. For a magnetic loop, the noise voltage arises from thermal fluctuations and is given by $\bar{v}_n = \sqrt{4kTR(\Delta f)}$, where R is the loop resistance. To make a calculation, we must choose a specific loop size: We select no. 20 wire and a diameter, D , equal to six inches. The signal voltage is given by $v = (\pi D)^2 f B/2$. Calculations were

performed for three different dipole source strengths, $m = 10^3$, 10^4 , and 10^5 A-m^2 . The value of 10^3 A-m^2 represents a rather modest source, while $m = 10^4 \text{ A-m}^2$ is quite practical. Magnetic antennas with $m = 10^7 \text{ A-m}^2$ have been constructed [77]. The maximum range between boreholes is plotted as a function of detector noise in Figure 9.2. The symbols indicate the maximum ranges that can be achieved by specific types of detectors. The magnetometers are characterized by their inherent noise level (Table 9.1) and by a detector bandwidth of either 0.1 or 0.025 Hz. The magnetic loop is characterized by $Q = 100$ and a frequency of either 10 or 100 Hz. A range of several hundred meters can be attained with several different types of hardware. The departure of some of the calculated points from the straight lines indicates that atmospheric noise is beginning to limit the range. Thus, the range cannot be extended to arbitrarily large values by building a noise-free transducer. It is thought that the most expeditious way to boost range is to increase the source strength.

9.3 SUMMARY

By making measurements of the a.c. magnetic field arising in one borehole from a solenoid located in another borehole, it is possible to determine the relative positions of the two boreholes. By using sensitive magnetic field detectors, bandpass filtering, and a magnetic source of moderate strength, the measurement of borehole separations of 200 to 500 meters appears feasible. The implementation of the magnetic ranging technique will require a considerable engineering effort, both in terms of hardware design and mathematical data reduction procedures. Nonetheless, the concept appears quite viable.

Figure 9.2. Maximum range of magnetic surveying technique. The range depends upon the detector design, the magnetic source strength, atmospheric noise, and the data inversion process (the signal-to-noise ratio). The departure of the calculated points from the straight lines indicates that atmospheric noise is beginning to limit the range.

SECTION 10

REFERENCES

1. W. T. Holser, et al., "Radar Logging of a Salt Dome," Geophysics Vol. 37, No. 5, Oct. 1972, pp 889-906.
2. R. Stewart and R. Unterberger, "Seeing Through Rock Salt with Radar," Geophysics, Vol. 41, No. 1, Feb. 1976, pp 123-132.
3. J. Cook, "Radar Transparencies of Mine and Tunnel Rocks," Geophysics, Vol. 40, No. 5, Oct. 1975, pp 805-885.
4. D. Moffatt and R. Puskar, "A Subsurface Electromagnetic Pulse Radar," Geophysics, Vol. 41, No. 3, June 1976, pp 500-518.
5. L. Dolphin, R. Bollen and G. Oetzel, "An Underground Electromagnetic Sounder Experiment," Geophysics, Vol. 39, No. 1, Feb. 1974, pp 49-55.
6. J. Fowler, personal communication, Ensco Inc., Springfield, Virginia.
7. J. Condon, R. Meyers and J. Snodgrass, telephone communication, Bureau of Mines, Denver, Colorado.
8. R. Lytle and E. Laine, "Design of a Miniature Directional Antenna for Geophysical Probing from Boreholes," IEEE Transactions on Geoscience Electronics, Vol. GE-16, No. 4, Oct. 1978, pp 304-307.
9. J. Stratton, Electromagnetic Theory, McGraw-Hill, New York, N.Y., 1941.
10. G. Keller, et al., "Investigations of the Physical Properties of Low Porosity Rocks," Appendix K of Federal Highway Administration Report FHWA-RD-77-11, A New Sensing System for Pre-Excavation Subsurface Investigations for Tunnels in Rock Masses, Vol. II, pp 317-371.
11. M. Campbell and J. Ulrichs, "Electrical Properties of Rocks and Their Significance for Lunar Radar Observation," Journal of Geophysical Research, Vol. 74, No. 25, Nov. 1969, pp 5867-5881.
12. M. L. Crawford, unpublished work performed at the National Bureau of Standards.
13. D. Keough, C. Smith and M. Cowperwaithe, Constitutive Relations from In Situ Lagrangian Measurements of Stress and Particle Velocity, Defense Atomic Support Agency Report DASA-2685, Jan. 1971.
14. D. Ellerbrach, unpublished data, National Bureau of Standards, Boulder, Colorado.

REFERENCES (Cont'd)

15. R. Lytle, Measurement of Earth Medium Electrical Characteristics: Techniques, Results, and Applications, UCRL-51479, Dec. 1973.
16. A. von Hippel, ed., Dielectric Materials and Applications, M.I.T. Press, Cambridge, Mass., 1966.
17. G. Olhoeft, Electrical Properties of Rocks, unpublished note.
18. J. Lawson and G. Uhlenbeck, ed., Threshold Signals, McGraw-Hill, New York, N.Y., 1950.
19. R. Berkowitz, ed., Modern Radar, Wiley, New York, N.Y., 1965.
20. W. Kerr, Propagation of Short Radio Waves, McGraw-Hill, New York, 1950.
21. J. Strong, Concepts of Classical Optics, Freeman, San Francisco, Calif., 1958.
22. Unpublished LASL notes.
23. F. G. West, et al., "Geophysical Logging in LASL Geothermal Test Hole No. 2," unpublished data, 1975.
24. M. C. Brown, et al., Hot Dry Rock Geothermal Energy Development Program: Annual Report, FY 1978, Los Alamos Report LA-7807-HDR, April 1979.
25. LASL (HDR) Project Staff, Hot Dry Rock Geothermal Energy Development Project - Annual Report, FY 1977, Los Alamos Report LA-7109-PR, Feb. 1978.
26. Schlumberger Log Interpretation Principles, 1979 Edition, Schlumberger Limited, 277 Park Avenue, New York, N.Y. 10017.
27. Schlumberger Induction-Electric Log, Well EE-1, 8-22-75.
28. Scott Keys, telephone communication, United States Geological Survey, Denver, Colorado.
29. J. H. Morgan and S. Gianzero, "Effects of Formation Anisotropy on Resistivity-Logging Measurements," Geophysics, Vol. 44, No. 7, July 1979.
30. L. E. Baker, et al., Well-Logging Technology and Geothermal Applications: A Survey and Assessment with Recommendations, Sandia Report No. SAND-75-0275, May 1975.

REFERENCES (Cont'd)

31. J. Zemanek, et al., "The Borehole Televiwer - A New Logging Concept for Fracture Location and other Types of Borehole Inspection," Journal of Petroleum Technology, June 1969, pp 762-774.
32. J. Mahoney, U.S. Steel Research, telephone communication.
33. P. Nelson, et al., Preliminary Technical Report on Geophysical and Mechanical Borehole Measurements at Stripa, Lawrence Berkeley Laboratory Report LBL-8280, May 1979.
34. M. B. Smith, Effect of Fracture Azimuth on Production with Application to the Wattenberg Gas Field, Society of Petroleum Engineers Report No. SPE 8298, 1979.
35. A. G. Blair, et al., LASL Hot Dry Rock Geothermal Project, Progress Report for July 1, 1975 to June 30, 1976, Los Alamos Report No. LA-6525-PR, Oct. 1976.
36. R. L. Morris, et al., "Using Compressional and Shear Acoustic Amplitudes for the Location of Fractures," Society of Petroleum Engineers Meeting in New Orleans, October 6-9, 1963, SPE Journal, June 1964.
37. J. Hearst, Lawrence Livermore Laboratory, personal communication.
38. T. Walker, The Interpretation of the Fracture Finder Micro-Seism Log, WELEX Corp. (Div. of Halliburton Co.) Report No. L-20, May 1964.
39. R. M. Potter, Hydraulic Fracture Initiation in Open Boreholes Identified by Geophysical Logs, 3rd Workshop, Geothermal Reservoir Engineering, December 14-16, 1977.
40. J. S. Wahl, et al., "The Dual Spacing Formation Density Log," Journal of Petroleum Technology, December 1964, pp 1411-1416.
41. W. S. Keys and J. K. Sullivan, "Role of Borehole Geophysics in Defining the Physical Characteristics of the Raft River Geothermal Reservoir, Idaho," Geophysics, Vol. 44, No. 6, June 1979.
42. M. Lamers, Measurement Requirements and Methods for Geothermal Reservoir System Parameter (An Appraisal), Lawrence Berkeley Laboratories Report No. LBL-9090, August 1979.
43. F. Oliver, Practical Instrumentation Transducers, Hayden, New York, 1971.
44. Schlumberger Cased Hole Application, 1975.

REFERENCES (Cont'd)

45. J. Tester, "Interwell Tracer Analysis of Hydraulically Fractured Granitic Geothermal Reservoir," Society of Petroleum Engineers of AIME, SPE 8270, October 1979.
46. J. P. Fritzsimmons, Precambrian Rocks of the Albuquerque Country, New Mexico Geological Society 12th Field Conference, Albuquerque, N.M., 1961.
47. J. H. Healy, et al., "The Denver Earthquakes," Science, Vol. 161, No. 3848, September 1968.
48. D. Rawson, Master's Thesis, University of New Mexico, 1957.
49. Office of Nuclear Waste Isolation, Battelle Memorial Institute, 1375 Perry Street, Columbus, Ohio 43201, Geosciences Division, J. O. Duguid.
50. P. Witherspoon and O. Degerman, Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns Program Summary, Lawrence Berkeley Lab. Report LBL-7049, May 1980.
51. A. Olkiewicz, J. Gale, R. Thorpe and B. Paulsson, Geology and Fracture System at Stripa, Lawrence Berkeley Lab. Report LBL-8907, February 1979.
52. P. Witherspoon, J. Gale, et al., Rock Mass Characterization for Storage of Nuclear Waste in Granite, Lawrence Berkeley Lab. Report LBL-8570, February 1979.
53. K. Waters, S. Palmer and W. Farrell, Fracture Detection in Crystalline Rock Using Ultrasonic Shear Waves, Lawrence Berkeley Lab. Report LBL-7051, December 1978.
54. P. Witherspoon, N. Cook and J. Gale, Progress with Field Investigation at Stripa, Lawrence Berkeley Lab. Report LBL-1055a, February 1980.
55. Atomic Energy of Canada Limited, Whiteshell Nuclear Research Establishment, Pinawa, Manitoba, Canada, ROE 110, Applied Geoscience, N. Soonawala.
56. M. Dence and W. Scott, The Use of Geophysics in the Canadian Nuclear Waste Management Program with Examples from the Chalk River Research Area, Atomic Energy of Canada Limited Report TR-102, March 1980.
57. C. Huang and J. Hunter, The 1978 Progress Report on the Seismic and Downhole Surveys at the Chalk River and Whiteshell Research Areas, Atomic Energy of Canada Limited Report TR-31, May 1980.

REFERENCES (Cont'd)

58. C. Huang and J. Hunter, Identification and Correlation of Tube Wave Events Shown on Borehole Seismograms, Atomic Energy of Canada Limited Report TR-32, May 1980.
59. C. Wright and K. Langley, Estimates of Crack Density Parameters in Near-Surface Rocks from Laboratory Studies of Core Samples and In Situ Seismic Velocity Measurements, Atomic Energy of Canada Limited Report TR-33, July 1980.
60. J. L. Davis, personal communication.
61. Federal Highway Administration, Office of Research, Washington, D.C. 20590, Don Linger.
62. Bureau of Mines, Federal Center, Denver, Colorado, J. Condon, R. Meyers, J. Snodgrass.
63. L. Rubin, J. Fowler and G. Marino, Multiple Borehole Radar, Final Report, Vol. 1, NSF (RAND) Grant No. APR 76-03300, June 30, 1978.
64. Ensco, Inc., Earth Sciences and Systems Division, 5408A Port Royal Road, Springfield, Virginia 22151, J. Fowler.
65. J. Coons, C. Schafers and J. Fowler, Experimental Uses of Short Pulse Radar in Coal Seams, Annual International Meeting and Exposition of the Society of Exploration Geophysicists, New Orleans, Louisiana, November 1979.
66. J. Fowler, Subsurface Reflection Profiling Using Ground-Probing Radar, SME-AIME Fall Meeting and Exhibit, Tuscon, Arizona, October 17-19, 1979, (Preprint No. 79-341).
67. S. Suhler and T. Owen, Evaluation of Geologic Structure and Engineering Properties of Ground Using a Borehole Electromagnetic Reflection Technique, Federal Highway Administration Order No. 7-3-0074, March 1978.
68. S. Suhler, et al., A Combination Resistivity, Seismic, and Electromagnetic Geotechnical Borehole Probe System, Interim Technical Report, Federal Highway Administration Contract DOT-FH-11-9323, March 1979.
69. Southwest Research Institute, 6220 Culebra Road, San Antonio, Texas 78284, T. Owen.
70. D. Northrop and C. Schuster, ed., Enhanced Gas Recovery Program, Third Annual Report, Sandia Laboratories Report SAND-79-0056, March 1979.

REFERENCES (Cont'd)

71. C. Schuster, Sandia Laboratories, Albuquerque, N.M., personal communication.
72. Unpublished test results.
73. T. Moore, L. Rorden and C. Kwong, Borehole Location System Concept Demonstration Tests, unpublished test results sponsored by the Bureau of Mines.
74. C. Russell, "ISEE 1 and 2 Fluxgate Magnetometers," IEEE Transactions on Geoscience Electronics, GE-16, No. 3, July 1978, pp 239-242.
75. A. Frandsen, B. Connor, J. Van Amersfoort and E. Smith, "ISEE-C Vector Helium Magnetometers," IEEE Transactions on Geoscience Electronics, GE-16, No. 3, July 1978, pp 195-198.
76. E. L. Maxwell, "Atmospheric Noise from 20 Hz to 30 kHz," Radio Science, Vol. 2, No. 6, June 1967, pp 637-644.
77. L. Rorden, personal communication.

APPENDIX A

FRACTURE MAPPING FROM THE SURFACE USING TILT MEASUREMENTS

A.1 EXISTING CAPABILITY

M. D. Wood, Inc., offers a commercial service employing surface measurements for determining the azimuth of vertical fractures. A circular array of shallow-buried tiltmeters is usually used to measure the rotation of the earth's surface produced by a fracture at depth. For a vertical fracture, the maximum surface tilt is orthogonal to the fracture plane and occurs at a distance on the surface equal to 0.38 times the depth of the fracture. The azimuthal variation in signal strength around the array allows the strike of the fracture to be inferred. Whether or not uncertainties in the determination of azimuth arise from a non-vertical dip or from multiple fractures has not been tested. Signal processing is used to remove the effects of cyclical disturbances such as earth tides and diurnal heating. Based on the internal consistency of the data, aperiodic or random disturbances such as weather fronts have a negligible effect on the final answer. It is crucial to ensure that the fracture signal is not contaminated with noise having the same spectral energy content as the fracture signal itself. For example, fracture inflation must occur within a time that is short compared to natural cyclical fluctuations, i.e., one-quarter of one day. Background noise data should be acquired over a period of several days (perhaps as much as ten days), which spans the time of fracture inflation. With current techniques, $1/R^2$ fall-off in signal strength limits the depth of hydraulic fracturing to about 10,000 feet. Based on Wood's reports of (i) successfully intersecting a fracture at the predicted location with a second borehole, and (ii) agreement of azimuth determinations using oriented core as an independent check, the technique appears successful.

A.2 IMPROVEMENTS IN TECHNIQUE

Wood has suggested that the maximum mapping depth could be extended by (i) employing a linear array of tiltmeters and stacking the data, or (ii) burying the sensors. A linear array can be used effectively only if the fracture azimuth is known fairly well prior to laying out the array. Thus, to lay out

a linear array for working at great depths, it would first be necessary to produce a hydraulic fracture at a shallow depth, say 9,000 feet, determine the strike and then assume that the strike does not vary rapidly with depth. The success of the method rests on the validity of this last assumption. Linear arrays have been used, but stacking to enhance signal strength has not been employed. Burying the sensors would allow at least a one-to-one increase in fracture mapping depth, but techniques for the remote emplacement of tiltmeters have not been tested by M. D. Wood, Inc. In addition, extant sensor packages have not been designed to work at temperatures and pressures in excess of surface ambient.

A.3 FRACTURE EXTENT DETERMINATION USING THE WOOD METHOD

A.3.1 Existing Capabilities

At the present time, Wood's technique has been employed only in bedded sedimentary strata where determining the vertical extent of fracturing has not been of commercial interest. No proven capability exists to map the vertical size of a fracture in a granitic medium.

A.3.2 New Methods Required

If the vertical extent of fracturing can be inferred from tiltmeters, then a model fitting process is almost assuredly required. Additional work is needed to assess the likely success of such an endeavor.

A.4 SUMMARY AND RECOMMENDATIONS

Wood's commercial tiltmeter service appears useful for determining the strike of a vertical fracture to depths of 10,000 feet. Working at greater depths requires a research and development program. A method for determining the vertical extent of fracturing using tiltmeters does not now exist.

Prior to employing directional drilling in a setting where fracture orientation is unknown, it appears worthwhile to use Wood's service in addition to borehole techniques to determine fracture azimuth. At the very least, the technique should provide an independent check of other geophysical measurements. Because of the potential usefulness of Wood's measurements, it is worthwhile to determine analytically if fracture extent can be inferred from surface tilt data.

APPENDIX B

NOMENCLATURE

A_e	effective area of receiver antenna
c_o	speed of light in vacuum
d	crack thickness
E	actual electric field at the point under observation
E_o	hypothetical field along the beam axis in free-space
$f(\theta, \phi)$	antenna pattern function
F	pattern propagation factor
G_t	transmitter antenna gain
h	height of an irregularity
k	Boltzmann's constant
m	dipole moment
$N(\sigma)$	density of scatterers (dimensionless)
P_1	power radiated by an isotropic antenna
P_2	power radiated by a directional antenna
P_r	signal power at the receiver
P_t	transmitter power
r	plane wave reflection coefficient
R	radar range; coordinate; electrical resistance
$\bar{S}_1$	average value of the Poynting vector at the target
$\bar{S}_r$	average value of the Poynting vector at the receiver
S_1	field strength or Poynting vector
T	temperature
z	coordinate

α	attenuation factor
β	phase constant
γ	complex phase constant
δ	skin depth
Δf	bandwidth
Δt	interval transit time
ϵ	permittivity
ζ	angle
θ	coordinate
Θ	beam width
κ_e	specific inductive capacity
κ_m	specific magnetic permeability
λ	wave length
μ	permeability
σ	electrical conductivity; radar cross section
$\sigma/\epsilon\omega$	loss tangent
τ	pulse length
ϕ	coordinate
Φ	beam width
ψ	grazing angle
ω	frequency, rad/s
$()_1$	rock
$()_2$	water
$()_j$	j^{th} element