MASTER

FRACTURE CHARACTERIZATION STUDY

U.S. Energy Research and Development Administration

Contract DE-AC 04-76ET15391

by

Robert F. Kehrman

April 1978

**WESTINGHOUSE ELECTRIC CORPORATION
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FORWARD

Part of DOE contract DE-AC 04-76ET15391 involves an engineering analysis of the Borehole Televiwer (BHTV) in an effort to estimate its performance under geothermal conditions. The analytical method consists of 1.) identifying physical parameters of the well which affect tool performance, 2.) contrasting these parameters for known petrochemical and anticipated geothermal conditions, and 3.) assessing net impact on geothermal BHTV performance.

An important and influential parameter is the sonic reflectivity of fractures which relates to fracture geometry. Therefore the need was recognized for characterizing fractures as they occur in geothermal wells and is the subject of this report. This work was carried out by R.F. Kehrman, contract geophysical consultant, at the request of J.W. Wonn, Principal Investigator.

1.0

INTRODUCTION

Under Contract DE-AC 04-76ET15391 with the U.S. Energy Research and Development Administration, Westinghouse Electric Corporation is engaged in the development of an acoustic sensor for applications in geothermal well logging. Task 1, which was completed in March 1977, was a survey of users of acoustic geothermal well logging tools. The purpose of the survey was to establish which particular logging tool or combination of logging tools should receive the highest priority for development during subsequent tasks. The result of Task 1 was the recommendation that Task 2 (Sensor Development and Optimization) should focus initially on the high frequency sensors suitable for the Borehole Televiwer/Acoustic Caliper (BHTV/CAL) application.

The BHTV is designed to take an oriented acoustic picture of the inside of a well bore. A downhole scanner-transducer and a fluxgate magnetometer are rotated at 180 rpm about a common vertical axis. A narrow beam 2.5 MHz acoustic signal is emitted as a pulsed signal. This signal is reflected from the borehole wall and is detected by the transducer. Scattering due to irregularities in the wall geometry varies the amplitude of the received signal. This is represented by intensity variations in the output as displayed on the face of a recording oscilloscope. The magnetometer generates a triggering pulse for the sweep signal to orient the oscilloscope display for recording on photographic material such that the display always starts at the same azimuth points in the borehole. This provides a direct and descriptive reproduction of the borehole wall split along a known line.

Fractures appear as characteristic lines, and bedding planes appear as sinusoidal curves with a single maximum and minimum point providing dip information. The BHTV has been identified as being useful during all phases of geothermal development. It can be used to map fracture zones, bedding planes and other borehole wall manifestations of the geology. In addition, after casing, the BHTV can be used as an inspection tool to map cavitation, pitting, perforation plugging or enlargement, casing breaches and other production related parameters.

As presently configured, under ideal conditions, the BHTV can resolve fractures 1/32 inch (0.8 mm) wide. This resolution is a function of several borehole conditions such as fluid density, diameter and others. It is also a function of various electronic parameters as well as a function of the recording oscilloscope and photographic film used to record the BHTV log.

One objective of Task 2 and the purpose of this report is to determine if the resolution of the BHTV is sufficient resolution for geothermal application. In making this determination, it is necessary to characterize fractures as they occur in geothermal drill holes. Much of the technology used for fracture characterization such as the BHTV in geothermal wells originated in the "oil patch." However, the problems associated with geothermal production vary from those encountered in oil wells. In the latter case, the actual resource is the fluid being removed. Therefore the problem is one of pumping the fluid out of the formation at whatever rate is possible and practical. In the case of geothermal resources, however, the fluid merely is a carrier for the resource (heat). In this case, removal of the heat depends on factors such as rate of fluid transmission through the formation and the total rock surface area exposed to the fluid. As a result, fracture distributions and the contributions of fractures to total permeability are extremely important to geothermal production.

In characterizing geothermal fractures, this report will first discuss the origin, nature and significance of fractures in general. Next, discussions will be directed toward the designation and classification of fractures. Next, some typical fracture measurement techniques will be discussed. Finally, geothermal fracture systems will be investigated and correlations will be made to determine which fracture technologies from oil field work are applicable to geothermal systems. This information will then be related to the BHTV to define resolution requirements and conditions which may be expected to affect resolution.

2.0 FRACTURES - ORIGIN, NATURE AND SIGNIFICANCE

A fracture is defined in the Glossary of Geology (1) as: "A general term for any break in a rock, whether or not it causes displacement, due to mechanical failure by stress. Fracture includes cracks, joints and faults." Researchers (2) have shown that fracturing in rock takes place beginning at grain boundaries. They conclude that the smallest fractures, known as "Griffith cracks" are equal in length to the maximum grain diameter. Griffith (3) postulated that a brittle material contains sharp flaws before stress is applied. When stress is applied, certain of these flaws enlarge and spread, thereby propagating the fracture. Observations indicate (4) that on a microscopic scale, these flaws are the grain boundaries themselves.

These Griffith cracks, which appear to be the origin for larger dimension fractures, have dimensions estimated at 100 Å wide and 1000 Å deep (2). Fractures, then can range in size from the dimensions of Griffiths cracks to those of faults depending upon the present and historical stress regimes. The thickness or separation of a crack is principally a function of the difference between external stress and pore pressure or the effective stress (2). Experiments performed in the laboratory on quartzite (2) indicate that fractures generally closed to about 3 μm in thickness when unloaded. Theory predicts that when under stress the width was substantially greater. Volumetric ratios of unstressed volume to stressed volume were observed to be on the order of 19% implying that the 3 μm width may have been as large as 10-15 μm under maximum stress.

This implies that as long as the stress remains unrelieved, the fracture will maintain some width which, it has been shown (2), is a function of the other dimensions of the fracture and the effective stress. However, since the hydrostatic pressure gradient is, in general, about one-half the geostatic pressure gradient, as shown in Figure 1, one would expect most fractures to normally be closed unless one of the following conditions exists:

- a. Abnormally high hydrostatic pressure.
- b. Fracture "filling" or "proping" due to foreign material injected in an open crack

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Figure 1 Graph showing the estimated reservoir pressure versus depth for over 100 wells in a group of Gulf Coast oil fields. (Ref. 5)

- c. Transverse or shear movement along the fracture.
- d. Weathering or chemical enlargement along fracture planes.

Any of these conditions may occur in a geothermal reservoir.

Fractures, resulting from brittle fracture of rock can be either of two types. These are shear fracture, which is typically the result of compressive stress and extension fracture which appears typically as a result of uniaxial extension. Typical fracture types are shown in Figure 2. Rupture surfaces from extension are characteristically rough and clean with little detritus. Simple surfaces of shearing are characteristically smooth with considerable detritus. Furthermore, discontinuities formed in shear are in general much more susceptible to alteration than are those formed in extension.

Fractures in rock materials are significant for a number of reasons. First, fractures have a definite effect on the mechanical properties of rock materials. In general, fractured materials are weaker and are more prone to weathering and other mass wasting processes. The effects of cracks on the elastic properties of rocks have been summarized by Jaeger and Cook (2) as follows:

- (a) The effective Young's modulus of a body containing open cracks and cavities is less than the intrinsic Young's modulus of a solid body.
- (b) The effective Young's modulus of a body containing closed cracks is less than its intrinsic Young's modulus if the surfaces of the cracks slide past one another.
- (c) Closed cracks which have undergone sliding do not slide in the opposite sense immediately after the load is reversed.
- (d) The effective Poisson's ratio of a body containing equidimensional cavities is less than the intrinsic Poisson's ratio of a solid body.
- (e) The effective Poisson's ratio of a body containing very flat, open cracks is less than its intrinsic Poisson's ratio.
- (f) The effective Poisson's ratio of a body containing closed cracks is greater than its intrinsic Poisson's ratio. In most rocks, voids, open cracks, and closed cracks of different and often random orientations are present. The behaviour of rocks in the first two regions of the complete stress-strain curve, shown in Figure 3, can be attributed to the effects due to these. The increasing slope of the stress-strain curve of very flat open cracks; the linear part of the second region with a slope defining the effective Young's modulus is probably

Figure 2 Types of Fractures (Ref. 2)

Figure 3 The Complete Stress-Strain Curve for Rock (Ref. 2).

due to the surfaces of these and other closed cracks sliding past one another; the initial slope of the stress-strain curve at the start of unloading provides a measure of the intrinsic Young's modulus of the rock, unless open voids are still present; the modulus decreases progressively as unloading proceeds and increasing numbers of cracks slide in reverse; the strain at zero load provides an indication of the amount of inherent compressive stress across crack surfaces in the rock; small stress changes superposed on the major loading and unloading cycle at any point are generally insufficient to cause sliding of crack surfaces and provide a measure of the intrinsic elastic properties. Corresponding changes in Poisson's ratio can be expected. Thus, the slope of the early part of the stress-strain curve for rock, the hysteresis observed in loading and unloading cycles, and the differences between static and dynamic moduli can be explained in terms of phenomena associated with the existence of cracks and cavities.

If the fractures are filled with fluid and are interconnected, then the strength of the rock is further reduced by the pressure of the fluid within the fractures and pores.

One graphic example of the effect of fractures on the strength of rocks, which has direct application to current geothermal experiments in dry hot rock areas, is the description of hydraulic fracturing experiments in the laboratory and in drill holes. If liquid is pumped into a borehole to a sufficient pressure, the tangential stresses in the surface of the hole due to the external stresses and the pressure will become tensile, and extension fracture will occur if this stress exceeds the tensile strength T_0 of the material. A joint or fissure intersecting the hole which is held 'closed' by the initial compressive stress field may be 'opened' by tensile stresses when internal pressure is applied. For example, for a number of underground drill holes into Rand quartzite the holes would not accept water at pressures below 1.5-2.5 times the overburden pressure, but at some pressure in this range would suddenly take water quite freely (2).

Another area where fractures are significant is illustrated in Figure 4. In such a case, fractures and joints are important types of secondary porosity. The brittle reservoir rocks which show fracture porosity include limestones, dolomites, cherts, shales, siliceous sedimentary rocks,

Figure 4 Idealized Section Showing how Fractures Aid in Increasing Permeability. Solutions Passing Through the Fractures Dissolve the Wall Material and Widen the Fractures Which Connect Otherwise Isolated Cavities and Pores.

igneous rocks, and metamorphic rocks. Interbedded shales, sandstones, and limestones may show selective fracturing in certain beds. Since fractures afford channels for the movement of water, they are likely to be enlarged and modified by solution. They frequently combine with other types of both primary and secondary porosity to make a complex porous pattern; in fact, the presence of fractures often changes the permeability from millidarcies to darcies (3 orders of magnitude).

The final significance of fractures in rocks is that they generally are the result of past or present tectonic forces within the rock mass. As such, they provide a permanent record of the directions in which such forces were applied or are currently being applied.

3.0 FRACTURE DESIGNATION AND CLASSIFICATION

Fractures may be and have been classified in many different ways. In the previous section, a classification as to causative stress type was mentioned. According to Underwood and Lachel (7):

"...there are not any distincting and generally accepted rules or nomenclature for engineering purposes..."

for the classification of discontinuities. They suggest, however that three criteria be used which will aid in the recognition of such features. The three criteria are:

- a. Scale - based on width and spacing.
- b. Character - based on smoothness and the properties of filling materials or coatings.
- c. Strength for Deformability - based on field and laboratory measurements.

For this study, only a. and b. are considered significant.

In classifying according to scale, Underwood and Lachel suggest five classes as shown in Figure 5. Microfissures are included and are usually considered a rock type characteristic. They are flaws in the rock type rather than genuine discontinuities.

Bedding planes and foliation partings are separations parallel to a mineralogically defined weakness direction in the rock. They are most often tight and rough.

Joints and seams are the discontinuities described as the "detailed discontinuity pattern." The term "seam" indicates a minor, often clay-filled zone with a thickness of a few inches. When occurring as a weak clay zone in a sedimentary sequence, a seam can be considerably thicker. Otherwise, seams may represent very minor faults or altered zones along joints, dikes, beds or foliation. Joints vary greatly in aperture, persistence, frequency and character. Many geologists will reserve the term for typical extension discontinuities, without any perceptible movement along the joint. Here, however, joint is used as a scale term and therefore also includes minor shear ruptures.

Figure 5 Classification of Discontinuities According to Scale (Ref. 7)

Faults are the major rupture zones encountered. Minor faults range in width from several inches to several feet; major faults from several to hundreds, occasionally thousands of feet. It is important to realize that most fault zones are the result of numerous ruptures throughout geological time, and that they quite often have other parallel discontinuities that decrease in frequency and thickness when moving away from the central zone.

In classifying fractures or discontinuities according to character, Underwood and Lachel suggest seven classes. These are:

- (1) Joints, seams and sometimes even minor faults may be healed through precipitation from solutions of quartz or calcite. In this instance, the discontinuity may be "welded" together. Such discontinuities may, however, have broken up again, forming new surfaces. Also, it should be emphasized that quartz and calcite may well be present in a discontinuity without healing it.
- (2) Clean discontinuities, i.e., without fillings or coatings. Many of the rough joints or partings have this favorable character. Close to the surface, however, it is imperative not to confuse clean discontinuities with "empty" discontinuities where filling material has been leached and washed away due to surface weathering.
- (3) Calcite fillings may, particularly when they are porous or flaky, dissolve. Gypsum fillings may behave the same way.
- (4) Coatings or fillings of chlorite, talc and graphite give very slippery, i.e. low strength, joint, seams or faults, in particular when wet.
- (5) Inactive clay material in seams and faults naturally represents a very weak material that may squeeze or be washed out.
- (6) Swelling clay may cause serious problems through free swell and consequent loss of strength, or through considerable swelling pressure when confined.
- (7) Material that has been altered to a more cohesionless material (sand-like) may run or flow into the drill immediately following drilling.

Using this classification system, it is possible to construct a quantitative plot indicating the relative detectability of discontinuities by two typical acoustic methods. This is shown in Figure 6 and can be used to put all of the classification parameters in perspective.

Figure 6 Relative Effects of Filling and Surface Characteristics on the Detection of Discontinuities with Acoustic and other Geophysical Techniques.

4.0

FRACTURE MEASUREMENT

Several drill hole logging methods have been devised for measuring the extent of fracturing. These have been listed in Table 1 in three categories. The first category includes methods which directly measure fracture distributions. The second category are tools which measure a parameter which directly indicate the presence of fractures. The final category are those tools which measure a parameter indirectly related to fracturing. Category I techniques are the most definitive, least ambiguous. Category III the least definitive, most ambiguous methods for locating fractures.

The importance of measuring fractures was discussed in a previous section. It was pointed out that fractures are important from a strength of rock standpoint and from a porosity/permeability and fluid production standpoint. This second consideration is perhaps the most significant as far as geothermal exploration and development are concerned. At the same time, it is important to realize that not all fractures will contribute to the porosity or permeability of a rock formation. Therefore, in considering fracture measuring techniques, one must designate the effect of fractures being measured. For example, the Category I techniques in Table 1 may be the most definitive measures of fracture distribution, however, they may give little information as to the fluid production of the rock. As a result, most fracture measurements made in the oil industry have been of the Category II and III types since exact knowledge of fracture size and distribution is of secondary importance to knowledge of actual or potential fluid production. The main products of measurements on oil well fracture systems are quantitative estimates of porosity and permeability. It is possible to relate these quantities to fracturing however little information is available which indicates size or dimension of fractures. In fact, in the literature surveyed within the context of oil production, the only reference or concern for fracture dimension pertains to whatever fracture size is necessary to enhance oil production.

TABLE 1

LOGGING TECHNIQUES WHICH MAY DEFINE FRACTURES

	<u>TECHNIQUE</u>	<u>PROPERTY MEASURED</u>	<u>COMMENTS</u>
Category I	BHTV	Acoustic Reflectivity of Borehole Wall	Best = 0.8mm. (present configuration). Depends on drilling fluid, fracture scale & character.
	Impression Packer	Mechanical (rubber) impression of borehole wall	Limited only by packer material, inflation pressure, borehole debris.
	Formation Sampler	Cores from formation	Unlimited, may not be "undisturbed."
Category II	Sonic log	Mechanical (bulk) properties of rock	Change in mechanical properties may indicate fracture density change.
	Sonic log	Permeability	Permeability changes many times due to fracture changes.
	Sonic log	Amplitude (1/Q, 1/f)	Amplitude reduced significantly over fractured zones.
	Flow meter	Fluid movement in and out of formation	Rate of flow min 5'/min. Zones of flow may indicate fractured zones.
	Spontaneous	Voltages within the borehole caused by flow	Rate of fresh/saline water flow into or out of hole may be related to fractures.
Category III	Resistivity	Resistivity of borehole wall rock	Bulk resistivity changes are related to many things including fractures.
	Gamma-Gamma Density	Compton scattered Gamma Radiation	Like resistivity - this parameter indirectly related to fractures.
	Caliper	Hole dimension	Washed-out or enlarged zones may be caused by rock weakened due to fractures.
	Temperature	Temperatures	Temperature changes may be due to fluid flow related to fractures.

A great deal of quantitative work on fracture size or aperture has been done by D. T. Snow (Ref. 8) in conjunction with studies of the Denver Earthquakes of the early to mid 1960's. Most of the work performed was on crystalline pre-Cambrian metamorphics and igneous rocks. Consequently, the results are not directly applicable to the sedimentary deposits which would be typical to hydrothermal deposits. This is due to the fact that in crystalline rocks, the assumption may be made that permeability is due to fractures only, while in sediments, other factors may contribute. This assumption is basic to Snow's work.

Snow's quantitative results are significant to this study, however, since they represent what could be considered the minimum fracture dimensions one may expect to encounter in any geothermal deposit. Therefore, the sizes observed by Snow would form a good basis for the maximum resolution of the bore-hole televiewer.

Snow, in describing the results of laboratory experiments on sandstone, points out that the minimum closure achieved on any fracture was never less than 25 microns. This is due to detachment and reorienting of grains during the deformation process.

Formulas were developed relating permeability to, among other things, fracture aperture. By measuring permeability, an effective aperture may be calculated for a given pressure. Some typical calculations are shown in Figure 7 to range from 230 microns down to less than 10 microns. This implies that in most cases, the fractures in crystalline rocks will be closed unless propped or inflated with pressure. Snow points out that the change in aperture is proportional to pressure change. The coefficient of proportionality is called the fracture modulus. Snow's relationship is

$$\Delta 2b = \frac{1}{C} \Delta p_f \text{ for horizontal fractures}$$

$$\Delta 2b^2 = \frac{1}{E/S + C} \Delta p_f \text{ for vertical fractures.}$$

Figure 7 Fracture Openings in Gneisses of the Front Range, Colorado, Computed from Injection Tests. (Ref. 8)

where:

- 2b = change in aperture
- P_f = change in fluid pressure
- E = Young's Modulus
- S = fracture spacing, and
- C must be determined empirically.

For typical values in Front Range rocks, C is on the order of $4.43 \times 10^4 \text{ gm/cm}^3$.

The above expressions imply that a pressure change on the order of 10 psi or $.7 \text{ kg/cm}^2$ will cause a horizontal aperture to open about 75 microns and a vertical aperture, with $S = 1 \text{ foot (0.3m)}$ and $E = 3 \times 10^6 \text{ psi}$ ($21 \times 10^4 \text{ kg/cm}^2$) to open up by 70 microns.

These relationships suggest that, if a rock is fractured, an effective way of insuring fracture detection using a BHTV logging instrument would be to "inflate" the hole during successive logging runs. Furthermore, the inflation pressure must be on the order of hundreds of psi in order to obtain fracture apertures within the 800 micron resolution range of the present televiewer.

5.0 GEOTHERMAL FRACTURE SYSTEMS

Production of geothermal energy from deep resource areas is very analogous to oil production. Both resources require vertically drilled bore holes which intersect the reservoir. Next, reservoir permeability must be sufficient and pressure gradients sufficient to cause a flow of the energy laden fluid into the drill hole. The geological regimes are similar since both oil and hydrothermal resources require an enclosed porous reservoir overlain by an impermeable layer which blocks the upward passage of fluid.

Some fracture characterization information is available in the open literature from several geothermal projects. These include the Los Alamos Fenton Hill project, the Marysville, Montana project, the Imperial Valley, California projects and Roosevelt Hot Springs, Utah project. Most of this information is only qualitative, however it does indicate the significance of fractures and gives one a "feel" for the dimensions of fractures.

A. Los Alamos, New Mexico Dry Hot Rock Project

The goal of the project was to drill into hot, unfractured granite and then to create a fracture hydraulically through which water could be circulated to remove the heat within the rock. As a result, fracture characteristics before and after fracturing are important. Analysis of cores from GT-2 indicated the following: (Ref. 9).

Megascopic fracture studies indicate a frequency of visible closed, or open and mineralized fractures of about 1 per 8 cm, locally increasing to 1 per 1 cm. There are horizontal, vertical, and roughly 60° dipping fractures. Petrographic and scanning electron-microscope and electron-microprobe studies indicate that the cores have undergone multiple microfracturing events followed by healing or sealing. Calcite is the most common fracture-filling mineral. Other minerals sealing fractures or in mineralized veins include muscovite, biotite, chlorite and pyrophyllite, siderite, hematite and rutile, saussurite or epidote, fluorite, tourmaline, and fine grained felsic minerals.

After fracturing, several attempts were made to characterize the hydraulic fracture. One successful attempt, using an impression packer in hole EE-1 indicated the fracture had a width of 1000 μm when the hole was inflated with 2000 psi pressure. Analytical determinations, based on laminar flow between the faces of the fracture, indicated that the fracture closes to about 40 μm when the inflation pressure is relieved.

B. Roosevelt Hot Springs, Utah, Hydrothermal Project

The core log in DDH1-76 describes the fractures in quartz monzonite as (Ref. 10):

... large (0.5 cm) fractures filled with green mineral and abundant pyrite. Downward, the granite (monzonite?) is fairly fresh. Biotite shows some alteration. Green mineral along fractures persists.

These observations were made at a relatively shallow depth (<200') as part of an alteration study.

C. Marysville, Montana

A suite of standard oil well logs was run at Marysville, indicating abundant fracturing. No quantitative estimates or direct measurements were made (Ref. 11).

D. Salton Sea, California

A study of rock chips revealed no fractures but grain sizes range from 1 to 100 microns (Ref. 12).

6.0 SUMMARY AND CONCLUSIONS

In this paper, it was pointed out that the bulk of fracture measurement and classification technology originate in the rock mechanics and oil industries. In the oil industry, interest is in the overall effect fractures have on net fluid flow into the borehole and not necessarily on the physical properties of the fractures themselves. In the rock mechanics industry, interest is on the net effect fractures have on bulk rock properties.

Studies by rock mechanics specialists have led to classification systems for fractures based on origin, size and character. Equipment development in the oil industry has led to hardware and techniques to measure fracture size, density, length and other properties.

Laboratory studies and field calculations indicate that in crystalline rocks, fractures may close to less than 10 microns while in sediments, fractures generally are 25 microns or larger. In either case, it may be possible to effect a larger fracture aperture by inflating the rocks several hundred psi.

Observations in geothermal wells are generally inconclusive from a quantitative standpoint. However, in each case, fracturing is generally present and a significant contribution to the overall flow of geothermal fluids. In the case of dry-hot rock geothermal production, the shape, size and orientation of fractures are extremely important parameters to determine.

The above observations lead to the following conclusions:

- Fracture distributions typically exist in geothermal reservoir rocks.
- Fractures contribute to the overall productivity of the reservoir.
- Fractures may range in minimum size from 10 to 25 μ depending on rock type.
- Fractures may be manifested by characteristic filling materials or weathered zones.
- Fracture measurement (characterization) should be possible using the present BHTV assuming the rock can be "inflated" to bring fractures above the resolution limit of the tool.
- A nominal target resolution figure of 1 mm (1000 μ) may be acceptable for most geothermal (hydrothermal) applications. Slightly better resolutions would be necessary for unpressurized dry-hot rock geothermal holes.

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