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Mapping Vertical Conductive Fractures:
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A MAGNETIC INDUCTION TECHNIQUE FOR MAPPING
VERTICAL CONDUCTIVE FRACTURES: STATUS REPORT

by

J. A. Landt, J. C. Rowley, J. W. Neudecker, and A. R. Koelle

ABSTRACT

Fracture mapping plays a vital role in the production of energy from hot dry rock. This report summarizes many fracture mapping techniques and discusses their merits. Of these methods, one based on magnetic induction appears to be well suited for the hot dry rock application. As of August 1977, the status is given here of the development of a fracture mapping instrument using magnetic induction. The basic analysis and electronic design have been completed. Detailed mechanical design and fabrication remain.

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I. BACKGROUND AND INTRODUCTION

The unique concept of extracting geothermal energy from hot dry rock is being actively investigated at Los Alamos Scientific Laboratory (LASL).¹ This concept hinges on completion of a fluid circulation heat transfer system between two boreholes in hot (250°C) rock, deep within the earth. Presently, the most attractive means of forming the required circulation path is through the use of conventional hydraulic fracturing. The fractured zone plays a vital role in the production of many present and potential energy resources such as oil and gas, in situ coal gasification, in situ oil shale production, and hydrothermal geothermal stimulation, as well as hot dry rock geothermal. However, only in the case of hot dry rock is detailed knowledge of the fractured region required for the production of energy. For this reason, many fracture mapping techniques have been considered and explored at LASL. One of these projects is the topic of this report. This is the vertical conductive fracture detector, which was originally conceived by Paul Kintzinger, Francis West, and Wade Johnson of LASL.

The fractures presently formed at a depth of about 3000 m in hard granite of 200°C at the Fenton Hill, New Mexico site appear to be nearly vertically oriented disks of several hundred meters diameter and several millimeters wide. The fractures are filled with water of moderate conductivity. The surrounding material is a high-resistivity granite. To be useful in the hot dry rock application, a fracture mapping technique must be capable of measuring this type of fracture. The vertical conductive fracture detector operates on differences in electrical conductivity between the fracture and the surrounding rock. As such, this mapper could be used in any well undergoing hydraulic fracturing and for leach mining applications.

Because of the potentially broad areas of applicability, and because ERDA is interested in helping nurture a geothermal industry, LASL has attempted to attract industrial participation in the mechanical design and construction of this instrument. The progress of this effort is also discussed in this report.

II. FRACTURE MAPPING TECHNIQUES

Unfortunately, no single technique presently exists that permits unambiguous detailed mapping of an entire fracture zone. Indeed, it is desirable that several techniques and methods are developed to define the orientation and geometry of the fractures. For the hot dry rock application, an instrument must be sensitive to the type of fracture described earlier, and if the instrument is to be lowered into the borehole, it must withstand 7×10^6 kg/m² (10 000 psi) and 275°C (527°F) in hot water and have a maximum diameter of 15 cm (6 in).

Several concepts with surface-located sensors have been used, are under development, or have been proposed. Some of these may be applicable to hot dry rock hydraulic fracture orientation detection; however, there are apparently serious problems.

A brief review of downhole fracture mapping techniques follows:

1. Control of Fracture Zone

Inflatable packers or perforations in casing can be used to control the zone (i.e., depth) where a fracture is started. These approaches have been taken at Fenton Hill, and they provide rough data on where the fractures were initiated at the borehole wall.

2. Spinners

These devices measure fluid flow and will map the borehole sections where fluid is entering or leaving the wellbore. Again, some rough idea of where the fracture intersects the borehole is obtained. This device has been successfully utilized once at Fenton Hill and they provide rough data on where the fractures were initiated at the borehole wall.

3. Tracers

Various tracers can be used to measure the fluid flow. Iodine tracers have been used at Fenton Hill. Radioactive surveys can determine if fluid is leaking in behind the casing and entering the formation at a level not originally intended; others can determine fracture to wellbore intersections. Colored dye

tracers have also been used at Fenton Hill to determine whether a circulation system had been established and to determine system parameters.

4. Electrical Surveys

These surveys respond to various electrical properties of the formation. Comparisons of measurements taken before and after fracturing have provided some general information about the regions influenced by the fracturing process, and often detect top and bottom of fracture if two wellbores are used.

5. Caliper

This device measures borehole diameter. A suitably designed tool could "feel" the fracture provided it has enough arms. A high-temperature caliper log has not yet been performed at Fenton Hill. Of the techniques mentioned so far, this is the only one that has the potential for giving the fracture orientation at the wellbore.

6. Impression Packer

This device is basically a packer but with a deformable surface that retains an impression of the borehole wall. The main drawbacks are the limited range of measurement, interpretation of the impressions on the open borehole wall, and temperature limitations.

7. Active Seismic

This category covers a wide variety of techniques. The sources include explosives, mechanical "bangers," magnetostrictive transducers, spark gaps, and other acoustic transducers. These techniques depend on "time-of-flight" measurements, measurements between S-wave and P-wave arrival, detection of reflections and, generally, the measurement of the influence of the fracture to the acoustic waves. The "wallbanger" and "detonator" techniques have both been employed at Fenton Hill, mostly to map the distance between boreholes, but also to get some information on the fracture.

Most acoustic techniques currently require two boreholes since the great depth prevents working from the surface. One technique presently being developed by the oil industry is designed to measure the intersection of fractures with the wellbore by using a circular array of acoustic transducers-receivers.

8. Borehole Televiwer

This perhaps could be included in the above category since it is essentially an acoustic "sonar" ranging of the borehole wall. It is presently able to detect a fracture wellbore intersection about 1 mm wide. The data are displayed on a TV tube and photographed. The main drawbacks are data interpretation and the lack of information deep into the rock. This technique has been used at Fenton Hill, and many "apparent" fractures were detected; most of them were probably natural. Therefore, before and after logs should be completed. Still, the device cannot tell which direction the fracture propagates away from the wellbore.

9. Passive Seismic

This technique depends on "microearthquakes" coming from fractures as they are pressured up.^{2,3} This technique has been developed at LASL and used at Fenton Hill, presently using two boreholes. Again, data interpretation hampers its effectiveness. Operation in a single hole is theoretically possible. However, there would be a region around the borehole that could not be mapped since the S and P waves could not be separated. The microearthquakes have not been detected at the surface.

10. Piezoelectricity

The "microearthquakes" mentioned above may also generate electromagnetic signals through piezoelectricity as the rock fails. These signals can be used to aid in the time-of-flight measurements of the passive seismic method. Additionally, triangulation techniques

could locate the source of the signals. This method is still in the conceptual stage, requiring development of sensors and data processing techniques.

11. Television

A downhole television system is under development by the oil companies. This device simply looks at the borehole wall. Development has been slow because applications are limited to those holes with clear fluid. Data interpretation and the limited depth of investigation are its primary faults. Only a low-temperature version is under development.

12. Induced Magnetic Anomaly

Magnetic material can in principle be injected into the fracture via the working fluid.⁴ The fracture geometry might then be determined by measuring the magnetic anomaly with very sensitive magnetometers and gradiometers and subsequent modeling. Complete mapping would require measurements at the earth's surface, although fracture orientation near the borehole could be determined from the borehole. This technique has not been developed.

13. Other Induced Anomalies

A radioactive material could be injected and detected with a collimated detector. This technique has not been developed. Material that "coats" the rock will coat the borehole as well and may obscure fracture detection. Other more exotic schemes can be thought of such as using high-energy particles or radiation and filling the fracture with an absorber. Such techniques are widely used in medicine.

14. Current Injection

Current injected in the borehole near the fracture will flow out into the fracture and affect potentials at the earth's surface above the fracture.⁵ This method shows great promise for shallow fractures (hundreds of meters deep), but it does not appear to give

- satisfactory results at fracture depths of several thousands of meters. It also appears that precise fracture geometry is difficult to obtain this way. For deep fractures, the electric and magnetic field can also be measured downhole. These measurements should provide fracture orientation with suitable modeling.
15. Focused Guard
An arrangement of electrodes (called a "focused guard") can be designed to focus direct current into the formation from a borehole.⁶ Basically, a measure of formation resistance can be obtained. If the guard is designed properly, the current can be focused into a thin vertical beam. This beam can be rotated and fractures detected as low-resistance regions. This concept has been laboratory tested, but no field instruments have been constructed.
16. Radar
It has also been proposed that an underground radar be used to map fractures. The main difficulties involved are the very shallow depths a radar investigates and the lack of sensitivity to a very thin fracture. Data analysis and interpretation will also be difficult.
17. High-Frequency Radio Measurements
Greater depths of penetration are obtained at frequencies lower than used in radar systems mentioned above.⁷ The technique relies on measurement of amplitude and phase of signals passing through or reflected from objects of interest. This technique has been used to find caverns, mine shafts, and map coal seams, clay-rock interfaces, and follow fluids injected in coal fields. The equipment is not yet ruggedized for the geothermal application, and generally more than one borehole is required.
18. Borehole Stress Measurements
It has been demonstrated (in shallow, low-temperature wells) that a fracture-relief stress gage can be utilized to define the state of stress around a borehole. The maximum and minimum principal stress directions can be determined, and therefore the fracture orientation inferred to be perpendicular to the direction of least principal stress.
19. Tiltmeters
Very sensitive, downhole tiltmeter (inclinometer) arrays can be used to sense local borehole deflections and distortions. Measurements taken before and after fracturing could be used to deduce fracture orientations, at least in the regions where a near-vertical fracture parallels a borehole axis.
20. Laser Interferometer
Measurements of small movements of a borehole wall as the hole is pressured or depressured can be used in principle to deduce fracture orientation. In addition to the tiltmeter method, borehole wall movement can be measured using a laser interferometry scheme.⁸ This involves holding optical corner reflectors tightly against the borehole wall to be used as motion sensors. Interferometry could detect very small displacements (on the order of the wavelength of the light used). Such a system will have many developmental problems in view of the intended environment.
21. Eddy Currents
A conventional induction instrument in present use by the oil service companies will respond to horizontal conductive fractures. This device was designated to measure the electrical conductivity of formations by measuring the eddy currents set up in the formations by a transmitting coil.^{9,10} This is a well-developed and very effective technique. The standard logging devices cannot map the fracture system at Fenton Hill, but it was proposed at LASL that this technique could be modified to perform that task. This modification is the subject of this report. Such an instrument will work from a single borehole and accurately map the fracture direction and

thickness within several meters of the borehole. The technique will work only in uncased sections of the hole, similarly to most of the electrical techniques discussed above. The initial efforts, supported by the hot dry rock project in FY-77, have demonstrated the basic feasibility of this proposed technique.

III. COMMERCIAL INDUCTION LOGS

The state of the art in induction logging tools permits determination of formation resistivity in the range from 0.1 to 1000 Ω -m. Present tools are limited to approximately 150°C. These devices are designed to operate best in oil-based (nonconductive) drilling fluid, and investigate into the formation approximately 3 m. The instrument measures secondary magnetic fields driven by eddy currents in the formation. The received signals are very small (on the order of tens of nanovolts or -160 dBV). Extreme care must be given to the electronics, grounding, shielding, mechanical deformations, etc. Present induction logs work very well as a result of many years of refinement and experience. A new geometry (i.e., a smaller diameter tool) can cost \$100K to \$200K to develop and field, and this without any major changes in design. The tools are designed to detect horizontal fractures or changes in the properties of horizontally layered formations.

IV. VERTICAL CONDUCTIVE FRACTURE ORIENTATION MAPPER

Serious consideration of using magnetic induction to detect vertical conductive fractures was the result of at least three items:

1. The failings of the other fracture mapping techniques.
2. The magnetic induction technique can perform the required mapping task, providing the information of the fracture orientation near the borehole.
3. The magnetic induction technique is highly refined in the industry. Good use can be made of this existing experience.

Because this instrument has major differences from its industrial counterparts, and because of

the initial specialized application, the hot dry rock geothermal project has funded the initial development efforts.

Summarized here are the use, theory, and design considerations of a high-temperature vertical conductive fracture mapper.

A. Theory of Operation

This instrument can be analyzed by techniques used to design commercial induction logging tools. These principles can be found in the literature⁹ and another report¹¹ describes the theoretical details of this magnetic induction fracture mapper.

The basis of operation can be summarized with several equations from electromagnetic theory. Consider the two-coil instrument shown in Fig. 1. The quasistatic electric field surrounding a small current loop (the upper coil) is

Fig. 1. Coordinate system for a two-coil coplanar induction log.

$$E_{\phi} = -j \frac{2\pi \times 10^{-7} f I_T N_T S_T}{r^2} \sin\theta \text{ v/m}, \quad (1)$$

where $j = \sqrt{-1}$, the conventional r , ϕ , and θ spherical coordinate system is used, f is the frequency in Hz, I_T is the current, N_T the number of turns, and S_T the area of the loop, and the medium is assumed to contain no magnetic material.

This electric field sets up currents in the surrounding conductive structures. This current distribution can be found from Ohm's Law for cases where the geometry contains the symmetry of E_{ϕ} :

$$\vec{J} = \sigma \vec{E} \text{ A/m}^2, \quad (2)$$

where σ is the conductivity of the surrounding medium. (If the geometry does not contain this symmetry, a more elaborate boundary value solution is required). Vector quantities are denoted by $\vec{}$.

The magnetic field at the receiving coil can then be found using Ampere's law:

$$\vec{H}(\vec{r}) = \int_V \frac{J \, ds \, \vec{dl}' \times (\vec{r} - \vec{r}')}{|\vec{r} - \vec{r}'|^3}, \quad (3)$$

where r is taken at the location of the receiver coil and r' is taken at the location of the eddy currents J .

Finally, the voltage induced in the receiving coil is

$$V_R = N_R \frac{\partial \phi}{\partial t}, \quad (4)$$

where ϕ is the magnetic flux linking the receiving coil. V_R can also be expressed in terms of the magnetic field:

$$V_R = j N_R S_R 8\pi^2 \times 10^{-7} f \vec{H} \cdot \hat{n}_R, \quad (5)$$

where N_R and S_R are the number of turns and area of the receiving coil, and $\hat{n}_R$ is a unit vector along

the axis of the receiving coil. Combining these equations for a homogeneous medium (i.e., the rock in which the fracture is formed)

$$V_R = - \frac{(8\pi^2 \times 10^{-7} f)^2}{8\pi R} N_T S_T I_T N_R S_R \sigma \text{ Volts}, \quad (6)$$

where R is the distance between the coils and σ is the conductivity of the rock.

A direct magnetic path exists between the two coils, giving rise to a "transformer" signal. This signal is

$$V_T = j \frac{(8\pi^2 \times 10^{-7} f)}{4\pi R^3} N_T S_T I_T N_R S_R \text{ Volts}. \quad (7)$$

This signal can be 1000 to 10 000 times as large as the signal arising from the rock or the fracture and, consequently, is eliminated by the addition of a third, "bucking," coil by choosing

$$\frac{N_T S_T}{R_T^3} = \frac{N_B S_B}{R_B^3}, \quad (8)$$

and

$$I_T = I_B, \quad (9)$$

as shown in Fig. 2. This also slightly reduces the signal due to the rock and the fracture.

A detailed analysis shows that the borehole fluid must be displaced. This leaves a rectangular hole in the fracture. The three coils are located in this hole. For this geometry, the signal due to the fracture is

$$V_F = (4\pi \times 10^{-7}) N_T S_T I_T N_R S_R \sigma t F \cos \beta, \quad (10)$$

where σ is the conductivity of the fluid filling the fracture and t is the thickness of the fracture, F is a function of the geometry of the problem

Fig. 2. Three-coil induction log geometry.

(i.e., coil locations) and β is the angle between the plane of the coils and the plane of the fracture. Typically, F is about 30 for the instrument presently under design.

It is the $\cos^2\beta$ term that permits the fracture direction to be mapped. The coils are rotated and a maximum signal indicates that the coils are parallel to the fracture.

Typical expected signals are:

"Transformer," $V_T = 1.13 \times 10^{-3} \text{ V}$

"Rock," $V_R = 4.6 \times 10^{-7} \text{ V}$

"Fracture," $V_F = 1.8 \times 10^{-7} \text{ V}$.

B. Instrument Design (Fig. 3)

Several aspects of the design have been mentioned earlier such as the three-coil configuration and a means required to displace the borehole fluid. The electronics will be required to be very stable and sensitive. Generally, synchronous phase-sensitive detectors will do this job the best. The earth's magnetic field will be used as a local ref-

erence direction. A commercial flux-gate magnetometer will provide this information in a similar manner to the system used in the US Geological Service (USGS) televiewer. The measurements will be digitized and transmitted to the surface on the wireline. For mechanical simplicity and reliability, two complete coil sets will be used and the coil rotation synthesized requiring no actual mechanical rotation. The measurement will sequence automatically upon application of power to the electronics. Borehole fluid will be displaced with an inflatable bladder. This bladder will be inflated with oil. The oil pumping system will be contained in the instrument. The electronics will be protected with a pressure housing and a dewar. The remainder of the instrument will be constructed to operate at temperatures under the existing pressure. The coil support section must be made of a high-temperature dielectric material.

This concept uses a wide variety of techniques presently in use. No breakthroughs are required, but no instrument has yet been constructed with all of these concepts combined. The design, construction, and intended instrument use is quite different from commercial induction logs. Indeed, no high-temperature induction logs are in existence.

V. PROGRESS TO DATE

Theoretical analysis (at LASL) has proceeded sufficiently to give confidence, but more is needed to optimize instrument design and assess the influence of various secondary factors.

Electronic efforts have proceeded (at LASL) to the stage of laboratory experiments and working breadboards.¹² Essentially, all of the preliminary design and electronics are completed with the exception of ruggedized construction.

A materials and vendor search was completed by E G & G, Inc.¹³ Materials and suppliers have been located for all of the items of major concern.

Mechanical design has progressed only through the conceptual stages. This design has been informally reviewed widely by the oil field service companies, and their comments have been appreciated and incorporated. Detailed mechanical design and construction awaits the outcome of a search for and selection of a subcontractor.

Fig. 3. Conceptual schematic of induction fracture mapper.

To fully utilize existing technology and experience in the well-logging industry, an active effort has continued to attract a service company to design and build the mechanical portion of the instrument. This industrial participation would also aid technology transfer of this instrument as well as stimulating interest in geothermal energy programs. The following companies were contacted and briefed on the magnetic induction fracture mapper: Dresser-Atlas, Birdwell, Schlumberger, Suntech, Sperry-Sun, Newtown Square, Gearhart-Owen, and Simplec.

All of these companies expressed interest, and many provided valuable time and suggestions. All of these companies, however, are very busy with their own work and, of the eight listed here, only one has expressed serious interest. These negotiations are continuing at present.

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