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FRACTURE DETECTION AND CHARACTERIZATION FOR GEOTHERMAL RESERVOIR DEFINITION

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Introduction

As more data from geothermal systems have been gathered and analyzed, there has been growing documentation and verification that fractures have a major effect on the performance of most geothermal reservoirs. In contrast to oil and gas reservoirs, geothermal resources are often encountered in rocks with low matrix permeability, such as volcanic formations and plutonic assemblages. Experience at several geothermal fields has shown that reservoir fluids are produced in important volumes only from narrow and infrequent zones containing fractures that are both open and well-connected hydraulically. In addition to their importance for well targeting, the location and characterization of open fractures within specific geothermal wells is also vitally important to engineers for interpreting pressure and flow test data, and for designing a proper reinjection scheme that avoids premature thermal breakthrough of injected fluids into production wells. This paper is a shortened version of an LBL technical report (Goldstein, 1984) in which the present state of technology in fracture detection and mapping is reviewed. Both papers present the author's opinion of present research needs.

Definitions

The word fracture used in this report encompasses the range of macroscopic openings and flow channels that would be classified as faults, fractures, joints, bedding planes, or breccia zones in a strict geological sense. For the purposes of numerical modeling and data analysis, a fractured rock is often treated as a single or set of planar or disc-shaped openings with constant apertures within an otherwise homogeneous and impermeable medium. This idealization of fracture morphology is testimony to the fact that our numerical codes and methods for interpreting field data are limited to the most elementary fracture.models. Within a given rock volume fractures may exhibit a wide range of lengths, apertures, orientations, and connectivities. Knowledge of fluid pressures, temperatures, composition of fracture-filling materials (including secondary or hydrothermal minerals [Elders, 1982]), and host rock properties are needed to describe the fracture in relation to the rock. Fracture apertures vary over many orders of magnitude. Those with apertures at least in the mm range and lateral dimensions on the order of ten's of meters are of primary interest. The larger openings develop as a result of magmatic processes, large-scale crustal deformation, and associated faulting.

Another type of fracture of major interest is the manmade hydrofracture. This type of fracture or fracture zone is created by pressurizing a well with an appropriate "frac fluid" to produce a hydraulic connection either to a nearby well or to natural fractures missed by the well.

Principal Goals

In the context of geothermal-energy development, there appear to be three areas where improved capabilities in fracture mapping are needed: exploration and reservoir delineation, reservoir modeling, and hydrofracture mapping.

1. Exploration and Reservoir Delineation includes siting and targeting of' exploration and development wells to intersect major fractures or zones of fractured rocks that serve as principal channels for flow of reservoir fluids.

2. Reservoir Modeling includes developing more realistic 3-D structural geologic models of geothermal reservoirs so that accurate estimates can be made of reservoir capacity, productivity, and longevity. Detailed data on fracture distributions is particularly important for designing reinjection schemes.

3. Hydrofracture Mapping includes developing more reliable methods for determining the orientation and length of hydrofractures created for stimulating poorly producing wells in hydrothermal systems.

Fracture Detection and Mapping Techniques

For the purposes of discussion, fracture detection and mapping techniques can be assigned to broad categories according to the physical point of observation or measurement. In this report we have chosen to group the techniques as follows: (1) remote-sensing

Table 1
Techniques for Fault and Fracture Mapping and Characterization

A. Remote Sensing Techniques
- Satellite imaging
  - Landsat multispectral scanner (MSS)
  - Thematic mapper (TM)
- Aircraft imaging
  - Low-sun-angle black and white
  - Color and false-color infrared (CIR)
  - Side-look radar (SLAR)
  - Thermal infrared scanner (IR)

B. Surface Techniques
- Geology
  - Detailed mapping of fractures
  - Mapping volcanic vents; dating eruptions
- Geochemistry
  - Volatile soil gases (He, Rn, Hg)
- Geophysics
  - Gravity, magnetics
  - Self potential
  - Electrical and electromagnetic
  - Surface deformation
  - Passive seismic - microearthquake detection
  - Active seismic - high resolution seismic reflection with P- and S-wave sources

C. Borehole Techniques (Single-hole)
- Geophysical (wireline) logs
  - Caliper, sonic velocity, fracture identification, borehole televiewer, acoustic borehole televiewer, natural gamma, induction (resistivity)
- Impression packer
- Well testing
  - Temperature, pressure and flowmeter
- Driller's logs
  - Mud losses, penetration rates
- Core drilling
- Tidal strain-pressure response
- Injection/production tests
- Very-low-frequency (VLF) EM
- Very-high-frequency (VHF) pulse radar
- Ultrasonic

Borehole Techniques (Cross-hole).
- Acoustic tomography
- Cross-hole VHF pulse radar (tomography)
- Multihole geologic-geochemical correlations
- Tracer tests
- Multi-well interference testing

D. Surface-to-Borehole Techniques
- Vertical seismic profiling
- Tube waves analysis
- Surface-to-borehole EM
- Mise-a-la-masse dc resistivity
- Magnetometric resistivity
- Fluid injection and monitoring at surface or in observation wells using geophones, electric- and magnetic-field sensors

techniques, (2) surface, (3) borehole (including borehole-to-borehole), and (4) surface-to-borehole (Table 1).

1. Remote-Sensing Techniques

Because of the long-standing interest by explorationists in satellite and aircraft imaging systems, most of the techniques listed in Table 1 are well known and in regular use (Lillisand and Keifer, 1979). The low resolution of the multi-spectral scanner (MSS) carried on the Landsat satellites make this technique suitable for mapping large-scale geologic features such as volcanic complexes, long faults, and lineations and curvilinear features. A mosaic of Landsat images over Italy reportedly showed an extremely close relationship between lineations, >100 km in length, and 75% of the known thermal springs (Barbier and Fanelli, 1976). These authors believe the lineations are structural breaks related to plate collisions and volcanism. The new seven-channel thematic mapper (TM) carried in the Landsat D' provides a resolution of 30 x 30 m or 2-1/2 times better than the MSS.

In spite of technical improvements in satellite imagery, resolution is far better using optical systems aboard aircraft. Low- and high-sun-angle (color and black and white) photography has been effective for locating subtle color changes and topographic dislocations due to faulting in alluvial sediments in Nevada (Wollenberg and Goldstein, 1977), at geothermal fields in the Philippines (Sanyal et al., 1982), and in Italy (Funiciello et al., 1982). Differences in soil moisture, hence plant vigor, and ground temperature due to fault zones have been discerned on infrared Ektachrome film (Babcock, 1971) and by means of thermal infrared IR scanning.

General limitations of remotely sensed images are that they do not reveal information on flat-dipping structures, and the data usually require "ground-truth" surveys. There is always the uncertainty of extrapolating surface features to reservoir depths. However, useful information have been obtained where remotely sensed data have been analyzed jointly with other geoscience data (see following section).

2. Surface Techniques

Geological Mapping

The mapping of faults, joint sets, cleavages and the mapping and dating of volcanic eruptions is fundamental to developing an idea of stress conditions and the orientation and location of fractures at depth.

Careful mapping and three-dimensional fault analysis was partially successful at the Redondo Canyon, Valles Caldera (Behrman and Knapp, 1980). Unfortunately, many of the major faults were found to be sealed by hydrothermal minerals at depth (Hulen, 1982; Hulen and Nielson, 1982), a fact which could not have been predicted from surface observations. On the positive side, there is evidence from the Lardarello Geothermal Field, Italy (Gianelli et al., 1978), The Geysers Geothermal Field, California (McLaughlin, 1981), and Coso Volcanic Field, California (Brophy, 1984) that structural interpretations based on surface mapping, aided by remote sensing, can indicate where highly fractured rocks are likely to occur. In these areas productive fractures have been intersected by drilling near the crests of anticlinal folds or in horst blocks, presumably because extensional near-surface horizontal stress keeps fractures open to an appreciable depth.

Geochemical Surveys

Chemical analyses of soils and soil gases are routinely used to help discern hydrothermal discharge areas. Anomalous concentrations of gases such as He, H_2, Rn and Hg, associated with hydrothermal-magmatic processes, have been used by many investigators to infer the presence of higher permeability zones. Geochemistry can often be useful in areas of recent cover and limited outcrops. Local hydrology may severely distort the anomalies.

Geophysical Surveys

Each geophysical technique has provided information on fluid flow paths or areas of faulting-fracturing at specific geothermal fields. This subject alone could fill volumes. Magnetics are routinely used in Iceland to delineate dikes, some of which have high permeability margins (Pálmasson, 1976; Flbvenz and Georgsson, 1982). Self-potential, electrical, and electromagnetic-sounding methods have (or appear to have) delineated resistivity anomalies associated with fluid flow along faults or zones of fractured rocks at a number of geothermal reservoirs, e.g., Cerro Prieto, Baja California (Lippmann et al., 1984), Roosevelt Hot Springs, Utah (Ross et al., 1982), Beowawe, Nevada (Zoback, 1979), and Dixie Valley, Nevada (Wilt and Goldstein, 1983). Among the less widely used electrical techniques, the "head-on" resistivity profiling, is claimed to be highly sensitive to subvertical, conductive fracture zones in Iceland (Flövenz, 1984) and the magnetometric resistivity method (MMR) is also claimed to be effective for detecting subvertical, thin conductors (Edwards, 1974). "Circular vertical electrical soundings" done in Yemen are reported to have determined the dominant direction of fractures in basement rocks (Stagalino et al., 1982). This technique is a quadripole Schlumberger sounding that provides information on apparent resistivity anisotropy, hence preferred directions of current flow.

It has been conjectured that geothermal areas are characterized by anomalously high levels of seismic noise due to subsurface processes such as thermal stress cracking and fluid flow along faults. Simple ground noise surveys have yielded high levels of noise over several geothermal fields [Taupo, New Zealand, (Clacy, 1968), The Geysers (Lange and Westphal, 1969), and at several locations within the Imperial Vallev (Douze and Sorrells, 1972)]. However, these high noise levels can be caused by acoustic resonance effects in the basin-filling sediments (Liaw and McEvilly, 1979). A more useful passive seismic technique for fault and fracture mapping is the microearthquake method (MEQ). In this technique a tight array of detectors is deployed to map microearthquake hypocenters, and to determine displacements and stress orientations associated with active faults. MEQ surveys have been conducted successfully at many geothermal fields, including East Mesa (Combs and Hadley, 1977), Coso (Combs and Rotstein, 1976), and Wairakei (Hunt and Latter, 1982). It has been found that swarm activity along active faults is unpredictable, thus necessitating equipment and techniques designed for long monitoring durations (over one month). Automatic data-acquisition and processing equipment is available to handle large-array seismic data (McEvilly and Majer, 1982).

Of all the surface geophysical techniques in use, high-resolution seismic reflection with modern 2-D and 3-D imaging techniques is receiving the greatest amount of attention, and there are reported cases where both flat and steeply-dipping faults were detected and properly imaged. How well the technology can be extended to geothermal environments remains largely unanswered. Because of the volcanic-plutonic rock assemblages and the hydrothermal alteration effects present in typical geothermal environments, it is an arguable point whether seismic reflection will have broad application to geothermal-reservoir mapping problems. However, the few published results to date from geothermal areas have been encouraging. Denlinger and Kovach (1981) showed that seismic reflection at Castle Rock Springs (The Geysers) was useful for detecting fracture systems within the steam reservoir, as well as for obtaining other structural-stratigraphic information. Blakeslee (1984) processed seismic-reflection data obtained by the Comision Federal de Electricidad over the Cerro Prieto Geothermal Field and was able to define subtle fault features and velocity variations believed related to tectonic and hydrothermal effects.

3. Borehole Technioues

Deep boreholes provide the chance to use a wide range of techniaues for fracture detection and characterization, particularly fractures intersected by the hole. Recovered cores, penetration rate and mud loss logs, and the suite of geophysical logs comprise a standard data set for determining the depth at which fractures occur, as well as information on their strike and dip. In recent years studies of cores and cuttings from geothermal wells drilled at Roosevelt Hot Springs, Cerro Prieto, Coso Hot Springs, and Valles Caldera have shown the hydrothermal alteration and trace-element geochemistry are useful techniques for identifying hot-fluid flow channels and for estimating past fluid temperatures and chemistries. All of this information is essential to a complete geometrical understanding of the fracture network within either individual stratigraphic horizons or the composite reservoir region (Keys, 1982).

Geophysical Well Logging

Good results in fracture detection have been reported from the use of geophysical well logs (Suau and Gartner, 1980; Keys, 1984). However, when used in high-temperature (> 200°C) geothermal wells, geophysical and other wireline devices have failed unless the hole was precooled with surface waters and the logging was completed rapidly, or unless the tools (electronics, seals, and cables) were hardened to withstand prolonged exposure to high temperature and corrosive conditions. There are few commercial tools that work at temperatures above 225°C, and most require an uncased well. There also exist a number of specialized high-temperature logging tools that will operate in the 250 to 275°C range, developed by government agencies and their research laboratories. Many of these tools are one-of-a-kind and therefore not generally available. For example, Fred Paillet of the Water Resources Division of the USGS claims to have geothermal well logging tools that are functional to a temperature of approximately 260°C for 8 hours operating time and a logging truck winch that holds 15,000 feet of a 7-conductor cable.

Geophysical logs give no information on fracture length, and they resolve fracture apertures poorly. Fracture orientation can be determined only by a few devices (dipmeter and acoustic televiewer, for example). Halfman et al. (1984) used wireline logs from over 100 wells to characterize the Cerro Prieto field, which is primarily controlled by stratigraphic units that communicate hydraulically via a few major faults.

Fracture Identification Logs® (a modified version of a dipmeter log) were run in the shallow cooler parts of the Baca geothermal wells (Valles Caldera) to determine whether fracture strike direction was related to well productivity (Union, 1982). Analysis showed an average strike direction roughly perpendicular to the major structure in the area, the northeast-striking Redondo Creek graben. No definite relationship between measured fracture orientation and well productivity could be discerned, but this could have been due to the limited sampling of fractures in the cooler part of the wells.

Well Testing Techniques

Because caliper and standard geophysical logs do not always identify the principal fluid-producing fractures, supplementary well testing is often done to distinguish open fractures from those that may be sealed by alteration minerals or mud filtrate (Keys, 1984). A review of some single- and multi-well-testing techniques for fractured reservoirs was given by Ramey and Gringarten (1982). In practice, spinner surveys are made in flowing wells, and pressure-temperature profiles are often run in shut-in wells. By using precise temperature measurements in boreholes and mathematical modeling, Drury et al. (1984) have described characteristic signals in temperature profiles caused by cold or hot water flow into or out of the borehole via fractures. In principle, small flow rates of $6 \times 10^{-8}\ m^3 s^{-1}$ can be detected in a 50-mm-diameter hole, but the resolution of the technique is reduced by various factors, such as noise in gradient measurements arising from flow between feed zones (Castaneda and Horne, 1981) and temperature anomalies due to thermal-conductivity variations near the wellbore.

If one can determine the number of fluid-producing fractures in an interval, it is sometimes possible to estimate a mean aperture. For example, for a geothermal well drilled into granitic basement, Benson (1982) estimated mean fracture apertures from a pressure-transient analysis. The pressure build-up curve indicated a permeability-thickness (kH) of ~ 8.4 x 10^{-5} md-ft for the open interval. Assuming that fracture aperture can be expressed by the cubic law (Snow, 1968);

$$kH = b^3/12,$$

Benson estimated a range of possible fracture apertures for assumed numbers of equally-sized fractures.

The tidal strain method (Hanson and Owen, 1982) was used at the Raft River Geothermal Field, and the principal directions of fracture orientation calculated are reported to be in good agreement with structure trends found from surface geology and Landsat images. The tidal interpretations are based in wellhead and downhole pressure measurements taken during conventional well-pumping tests. Wellhead data were obtained with commercially available pressure transducers; downhole data were taken with a temperature-compensated quartz pressure probe. Data analysis required separating the small tidal responses from barometric and pumping effects.

In-Hole Geophysical Techniques

A major unresolved problem in fracture mapping is the detection and mapping of a fracture zone missed by the borehole but occurring within tens of meters from the hole. On the assumption that a large aperture crack is a good reflector of high-frequency electromagnetic and ultrasonic waves, both in-hole VHF pulse radar and ultrasonic acoustic techniques have been evaluated and tested to some degree under controlled surface conditions, such as in cold, near-surface granitic rocks (Chang, 1984; Chang et al., 1984). Reflected signals from fractures have been observed, but the technology has not been extended to geothermal environments. There seems to be technical obstacles that need to be addressed. First, there is the common problem of temperature effects on electronic components, seals, cableheads, and cables. Second, there is the engineering problem of developing directional and steerable energy sources that will operate in the confines of a narrow wellbore. Lastly, there is the problem of identifying the signal sought from the clutter caused by other geological discontinuities (Hartenbaum and Rawson, 1980).

Cross-Hole Techniques

In situations where two or more closely spaced (< 30 m) wells are available, a great deal can be determined about major fractures or flow paths connecting pairs of wells. Well-to-well correlations of geologic and geophysical well log data are routinely done to identify, if possible, major through-going fractures. Because wells may not be close enough to provide much information on the inter-well distribution of fractures, tracer tests coupled to multi-well pressure-interference tests have been conducted. These tests are designed to ascertain whether flow paths exist between the wells and to develop a fracture model based on tracer breakthrough times and pressure responses between injection and observation wells (Bodvarsson, 1981; Bodvarsson and Tsang, 1982; Home, 1982; Pruess and Narasimhan, 1982; Gudmundson, 1984). For modeling tracer returns the main problem is that a flow geometry must be assumed, a priori. Thus, the geometric characterization of fast paths between wells remains uncertain (Pruess and Bodvarsson, 1984). Another problem may rest with the tracers used; e.g., tracer material may be lost due to adsorption, ion exchange, and chemical reactions with rock and pore fluids (Vetter and Zinnow, 1981). At this stage of tracer studies, we lack realistic numerical methods to model fluid-tracer transport through a fractured medium, as well as the appropriate chemical kinetic data to use in these codes to account for the water-rock reactions.

In response to engineering problems associated with tunneling and underground excavations, investigators have developed and tested crosshole (tomographic) techniques in which ultrasonic acoustic waves (Paulsson and King, 1980; King et al., 1984) or VHF electromagnetic pulses (Ramirez et al., 1982; Wright and Watts, 1983) are transmitted between sources in one well and a string of detectors in an adjacent well. Variations in velocity and amplitude of the direct wave between each source and receiver position can provide information on the density and (sometimes) the orientation of fractures. To date, most of the geotomographic work has been experimental and limited to holes only meters apart. The tools and interpretation techniques have not been extended to geothermal environments.

In contrast to the single-hole techniques, the cross-hole techniques do not depend on steerable, directional antennas. However, the eventual success of such techniques will require high-energy sources that can be used in geothermal wells. In addition, large lateral variations in velocity (≥ 10%) may occur, necessitating more complicated analyses accounting for curvature of the ray paths.

4. Surface-to-Borehole Techniques

The fourth category of techniques, are the surface-to-borehole methods, so named because the measurements require a combination of surface and in-hole sources and detectors.

Vertical Seismic Profiling

Vertical Seismic Profiling (VSP) is conducted using both P- and S-wave surface sources (usually mechanical vibrators) at one or more locations near the well. Direct and reflected waves are detected by down-hole geophones clamped to the well wall at intervals. VSP has been used mainly to trace seismic events observed at the surface to their point of origin in the earth and to obtain better estimates for the acoustic properties of a stratigraphic sequence (Balch et al., 1982). Gal'perin (1980) VSP research in the USSR, including recent results of 3-component VSP (P- and S-wave sources with 3-component detectors) to estimate Poisson's ratio.

While much of the interest in VSP has centered on better stratigraphic interpretations, particularly in areas where conventional surface-to-surface reflection surveys have not proved entirely satisfactory, VSP conducted by using multiple P- and S-wave sources around a well may resolve local structural discontinuities and fracture zones near the well. However, in this regard VSP may be considered experimental. At Fenton Hill, New Mexico, an S-wave shadow zone was discerned by VSP before and after a hydrofrac operation at 2300-feet depth (Fehler et al., 1982). On the basis of VSP data from three shot points, a finite-difference model showed that the shadow data fitted other information about the hydrofrac. However, due to the low-frequency S-wave source and the long wavelength of the S-wave (200 feet) in the medium, it would seem that the fractured region must have dimensions of at least 50 feet. This suggests that frac fluid invaded a large volume of rock, not simply a planar fracture and a narrow leak-off zone adjacent to the fracture.

A source of noise in VSP surveys comes from tube or Stonley waves, which are high-amplitude guided waves in the wellbore. Although they are excited mainly by the Rayleigh waves ("ground roll") crossing the wellhead (they are particularly severe if the source is close to the well), tube waves may also be excited by body waves impinging on fractures that intersect the wellbore (Cheng et al., 1982). Consequently, there has been some interest in developing methodologies to derive fracture-penneability information from the tube waves (Paillet, 1980). Crampin (1978, 1984, in press) and others have argued that VSP conducted with 3-component geophones might prove extremely useful for mapping the fractured conditions of rocks if one were able to extract seismic anisotropy information from the shear-wave splitting effect.

Mise-a-la-Masse Electrical and Electromagnetic Methods

The mise-a-la-masse resistivity techniques (Daniels, 1983) are applicable when a current electrode can be implanted directly into a subsurface conductor. The channeling of current produces a larger and more diagnostic surface anomaly. By mapping and interpreting surface potentials, one can then obtain a better 3-D picture of the conductor. This approach has extended information away from a well in a few known cases where a geothermal well has intersected a productive fracture zone (e.g., Kauahikaua et al., 1980: Tagamori et al., 1984). The well casing, energized with a very low-frequency square-wave current, serves as one electrode; the second current electrode is planted far from the well. Electric-field variations are mapped at the surface around the well by a closely-spaced grid of orthogonal electric dipoles. After a residual map is prepared to remove the effects of earth layering, the results are analyzed to reveal distortions caused by current channeling from the well casing into the conductive fracture zone.

Surface-to-borehole electromagnetics (EM) is a related method. One technique under study is based on inducing currents in a conductive fracture zone using a powerful low-frequency transmitter coaxial with the well. Diagnostic information on the fracture zone is obtained by running a magnetic-field detector in the well. Whether this technique will work in cased wells and whether a "crack" anomaly can be distinguished from a "thick" stratigraphic conductor are topics under study at LBL.

The magnetometric resistivity (MMR) method is similar in some respects to dc resistivity and EM methods. Whereas EM is directly sensitive to the conductor, MMR is sensitive to the resistivity contrast between the host rock and the feature sought. Surface-to-borehole MMR is carried out with a low-frequency, vertical grounded bipole source (a pair of current electrodes) in the well and a synchronous magnetic detector, usually 3 components, for mapping the field at the surface. Because the primary magnetic field is zero everywhere at or above the surface of a uniform earth, the measured magnetic fields reflect only current distortions caused by inhomogeneities such as a planar conductor (Nabighian and Oppliger, 1980; Edwards, 1984; Nabighian et al., 1984). The method is insensitive to topography, but requires good knowledge of receiver locations. MMR can be used in the cross-hole configuration (Edwards, 1984; Nabighian et al., 1984), but not in fully cased wells.

Other Experimental Techniques

Certain experimental techniques being evaluated for mapping hydrofractures may be applicable to shallow systems of natural fractures as well. In these experiments one attempts to make the fracture or fracture zone more detectable by pumping vast amounts of fluid with special properties into a packed-off interval of the well. Injection only or a combination of injection and backflow tests are made in conjunction with electrical, magnetic, and seismic monitoring at the surface and in observation wells with the objective of mapping the height, orientation and length of the fractured zone. In addition to the VSP experiment mentioned above, other efforts include:

1. Injecting a conducting fluid (e.g., acid) and measuring changes in self potentials by a surface electrode array.
2. Injecting a conductive fluid while energizing the casing with a low-frequency current and monitoring either the change of surface potentials by means of an electrode array at the surface (Hart et al., 1983) or magnetic field changes by surface and borehole magnetometers.
3. Injecting of a ferrofluid or magnetized particles and gel into a fracture and monitoring changes in the magnetic field at the surface or in observation wells. A shallow experiment has been performed (Wood et al., 1983) and a fundamental study has been conducted by LBL to determine whether the weak signal (in the milligamma range) from a "magnetic" fracture at large depths can be extracted and identified from the many noise sources (instrumental, natural fields, and vibrational-mechanical noise) encountered in the field.
4. Pressurizing a zone with water or an ordinary frac fluid and monitoring and locating discrete microseisms by a triaxial, high-temperature geophone package during injection and after the pumping is stopped (Pearson, 1981; Batra et al., 1984). Encouraging results have been reported at several hot dry rock sites: Fenton Hill, New Mexico (Pearson, 1981), the Carnmenellis granite, England (Batchelor et al., 1983), and the Yakedake Geothermal Field, Japan (Yamaguchi et al., 1984). The observed seismic activity is believed to be due, in major part, to shear failure along fractures and joints that is induced when the pore pressure exceeds the normal stress across the openings. Locatable microseismic events outline the general orientation of the fractured region. Experiments show that the fracture length and direction determined from microseismicity after the well is shut-in may not agree with the results of hydraulic measurements in nearby observation wells. This suggests that we are far

from total understanding the source mechanisms of the microseisms.

Research Needs

This review has indicated a number of research topics that would enhance the present Fracture Detection part of the DOE Geothermal Reservoir Definition Research Program. Without regard to funding level, priority, or cost-sharing with industry and other Federal agencies, we list below the more promising approaches and techniques.

1. Develop and compile case-history information on the relation of regional and local faults and stresses, determined from remotely sensed and surface measurements, to fault-fracture distributions and orientations within geothermal reservoirs. In conjunction with this work, research on fracture genesis and the statistical distribution of fractures seems appropriate.
2. Continue research on the joint application of high-resolution surface seismic reflection, vertical seismic profiling, and geophysical logging to the imaging of faults and fractured zones within geothermal reservoirs.
3. In conjunction with 2, extend the useful temperature range and increase the reliability of downhole instruments and packers. This work should concentrate on the more useful types of logs for fracture information; e.g., acoustic televiewer, acoustic velocity, high-resolution dipmeter, and various types of nuclear logs.
4. Continue research on techniques and interpretation of data from well injection/production tests and multiple-well interference tests for deducing fracture parameters.
5. Evaluate the technical feasibility of several experimental techniques for detecting and mapping fractures <u>not intersected</u> by a wellbore; e.g.,
   (a) surface-to-borehole EM and MMR,
   (b) in-hole EM (VLF and VHF pulse radar),
   (c) in-hole ultrasonic acoustic, and
   (d) geotomography,
   to fracture detection in the geothermal environment. Build and test prototype instruments for the more promising techniques.
6. Continue research on tracers and tracer techniques, including the development of better numerical methods to model macroscopic fracture flow, including provisions for chemical-reaction kinetics.
7. Evaluate the concept of extracting fracture information from tube waves and run experiments in wells that intersect fractures that have already been fairly well characterized.
8. Evaluate and test improved methods for mapping the length and orientation of hydrofractures.
9. Compare various surface electrical techniques for fault mapping (e.g., head-on resistivity, MMR) by means of field tests and numerical models.

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