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An Assessment of Current Technology, Research, and Research Needs

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November 1984

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 the typical oil or gas reservoir, geothermal resources are most 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 where a well has intersected 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 wellhead pressure and flow test data and for designing a proper reinjection scheme that avoids premature thermal breakthrough of injected fluids into production wells.

The detection and mapping of fractures and other zones of high permeability, whether natural or manmade, has been a subject of considerable economic and scientific interest to the petroleum industry (Kostura and Ravenscroft, 1977) and to the geothermal community (Geothermal Resources Council, 1982). Research related to fractured geothermal reservoirs has been conducted under several past DOE geothermal energy development programs, including the Geothermal Reservoir Engineering (LBL, 1977), Geothermal Logging Development (Veneruso and Coquat, 1979), Geothermal Log Interpretation (Mathews, 1980; Sanyal et al., 1980; Mathews et al., 1983), Exploration Technology (Nielson, 1979), and Drilling and Completion Technology (Kelsey, 1984). In 1984 Fracture Detection and Mapping was designated as a separate research component of the DOE Reservoir Definition Program. The need for a thorough re-evaluation of existing fault and fracture mapping methods and instrumentation was discussed in the Program's multiyear research plan (Molloy, personal communication, 1984) and agreed to in planning meetings with DOE Program Management. This evaluation is the first step toward formulating a sound and comprehensive multiyear research program.

In this paper we review the present state of technology in fracture detection and mapping. We outline the major problems and limitations of the "conventional" techniques, and current research in new technologies. We also 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

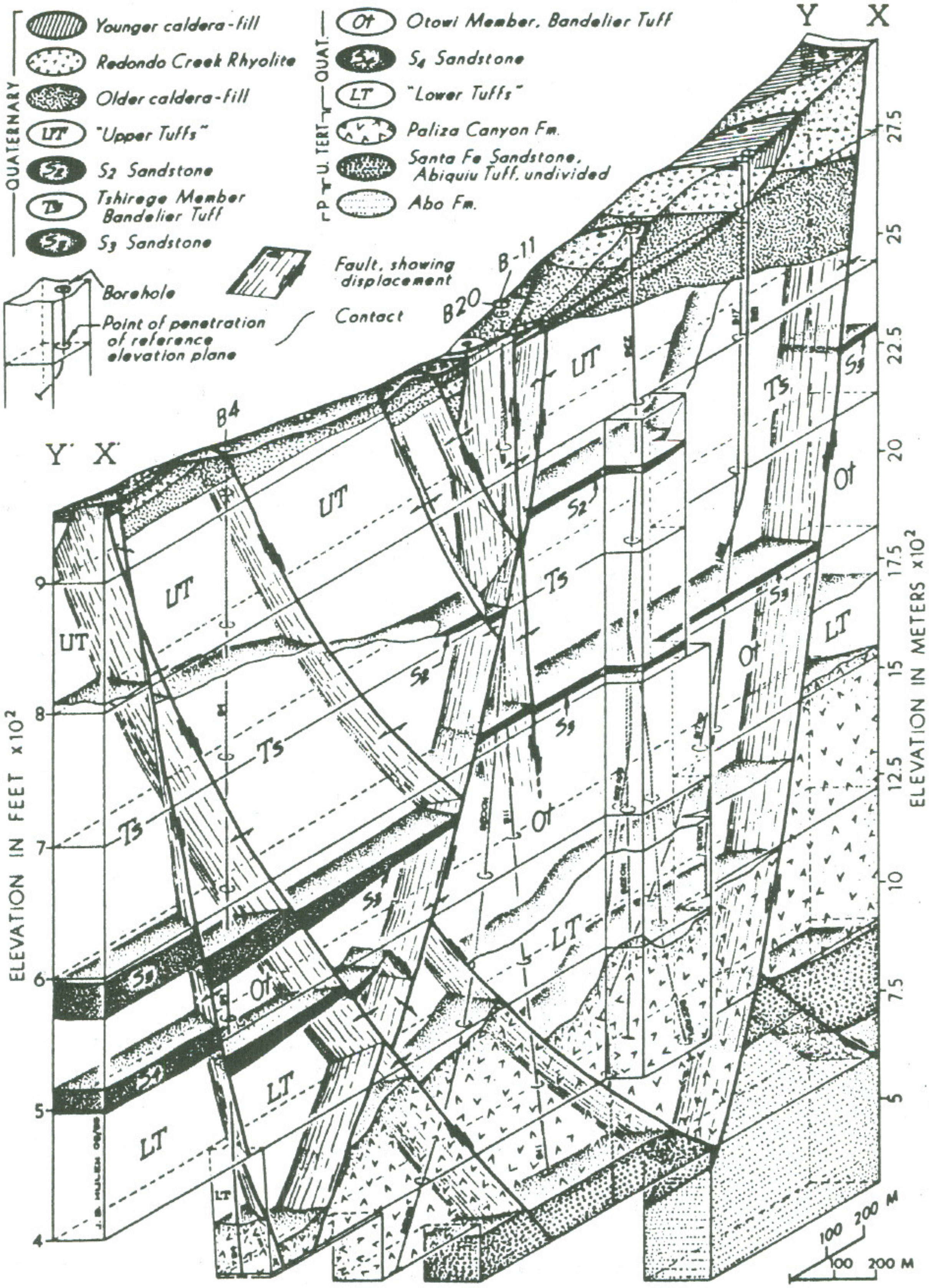

Figure 1. **Three - dimensional geological cross - section of the Redondo Creek area, Valles Caldera, New Mexico**

(after Hulen, 1982).

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.

Individual fractures and fracture networks may also be connected hydraulically to confined permeable stratigraphic features (thin sedimentary and volcaniclastic interbeds, flow breccias, and unconformities) from which they sometimes cannot be easily distinguished except by detailed subsurface analysis (Hulen, 1982; Sanyal et al., 1982). Figure 1 is a three-dimensional interpretation of the major stratigraphic and structural elements in the Redondo Canyon area of the Valles Caldera, New Mexico (Hulen, 1982). The figure shows the relationship between the various normal faults and the permeable sandstone units S_2, S_3, and S_4 within the otherwise low permeability Bandelier Tuffs (UT, Ts, Ot, and LT).

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 modelling, 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.

Methods of Approach to Fracture Detection and Mapping

In this report we have classified fracture detection and mapping techniques according to the physical point of observation or measurement, dividing the techniques into four categories: remote-sensing techniques, surface techniques, borehole techniques, and surface-to-borehole techniques.

1. Remote-Sensing Techniques provide regional and subregional information on potential locations of faults and fractures from analysis of satellite and aircraft imagery. For the most part this technology is mature, and considerable advances in data acquisition, processing, enhancement, and interpretation have been made.

2. Surface Techniques consist of detailed surface geological observations and subsurface inferences derived from geochemical and geophysical measurements.

3. Borehole Techniques consist of observations and measurements that can be made on cores, information gained during the drilling process, and detailed measurements made within individual wells or between adjacent wells (i.e., cross-hole techniques).

4. Surface-to-Borehole Techniques are techniques, usually geophysical, that require a combination of surface and borehole instrumentation to discern fractures and faults in the region around a well.

Appendix A lists and describes the various techniques that are routinely used for fracture mapping, as well as many techniques in an experimental or testing stage. The table is organized according to the four categories listed above. Some techniques may have been omitted, but we have made an attempt to search out and include all those reported in the recent literature. Appendix A includes information on the status of the technology, the approximate resolution of the techniques, and the state of development and limitations of the techniques. The discussion that follows amplifies points made in Appendix A.

1. Remote-Sensing Techniques

Because of the long-standing interest in mapping from satellite and aircraft heights by the geological community, and specifically by explorationists, many of the remote-sensing techniques listed in Appendix A are routinely applied to mapping large-scale geologic features (Lillisand and Keifer, 1979; Goetz et al., 1983). The low resolution of the multispectral scanner (MSS) carried aboard the Landsat satellites make this technique suitable mainly for mapping large-scale geologic features such as volcanic complexes, prominent long faults, and lineations and curvilinear features of tectonomagmatic origin. 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. Improved resolution will be provided by means of the seven-channel thematic mapper (TM) carried aboard the Landsat D′. Prixiel size of the TM is 30 x 30 m, or 2-1/2 times better than for 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 B&W) photographs have been effective for characterizing major fracture patterns (Blanchet, 1957) and for locating subtle color changes and topographic dislocations due to growth faults in alluvial sediments (Wollenberg and Goldstein, 1977). Air photographs have been used for fault mapping at many geothermal areas (Sanyal et al., 1982; Funiciello et al., 1982). Differences in soil moisture, hence plant vigor, and ground temperature due to leakage along faults have been discerned on infrared Ektachrome film (Babcock, 1971). Thermal IR scanning is also valuable for detecting cold and warm water discharge areas.

The general limitations of remotely sensed images are that they do not reveal information on flat-dipping structures, and the data usually require "ground-truth" follow-up surveys. There is always the uncertainty of extrapolating surface features to reservoir depths without additional studies. However, useful information has been obtained in geothermal areas where remotely sensed data have been analyzed jointly with other geoscience data (see next section).

2. Surface Techniques

Geological Mapping

The mapping of fractures associated with faults and folds (Stearns and Friedman, 1972) 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 area of the Valles Caldera (Behrman and Knapp, 1980). Unfortunately, many of the major faults there 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 direct 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 perhaps by remote sensing, can indicate where highly fractured rocks are more likely to occur. In all three 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 helium, hydrogen, radon and mercury, associated with hydrothermal-magmatic processes, have been used by many investigators to infer the presence of higher permeability zones. Soil gas anomalies may be extremely useful in areas of recent sediment and volcanic cover or where outcrops are limited. Local hydrology can distort and displace anomalies.

Geophysical Surveys

Each surface geophysical technique has provided valuable or confirmatory information on faults or fluid flow paths at specific geothermal fields. For example, magnetics are routinely used in Iceland to delineate dikes, some of which are bordered by zones of high permeability (Pálmasson, 1976; Flövenz 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 fracture rocks at a number of geothermal reservoirs, including 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 technique, a derivative of Schlumberger array profiling, is reported to be extremely effective for detecting subvertical, conductive fracture zones at geothermal fields in Iceland (Flövenz, 1984). The magnetometric resistivity method (MMR) is also reported to be effective for mapping subvertical faults (Edwards, 1974), but to our knowledge this method has not yet been used at a geothermal field. "Circular vertical electrical soundings" made in Yemen are reported to have determined the dominant fracture direction in the 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 Valley (Douze and Sorrells, 1972)]. However, these high noise levels can be caused by acoustic resonance effects in the basin-filling sediments and as such are related to the thickness of the unconsolidated 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 fault displacements and stress orientations and associated with active faults. MEQ surveys have been conducted successfully at many geothermal fields, including East Mesa, California (Combs and Hadley, 1977), Coso (Combs and Rotstein, 1976), and Wairakei, New Zealand (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). Regional stresses are determined by studying the characteristics of the larger ($M_L > 4$) regional earthquakes.

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 arguable 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 techniques applied to the steam system at Castle Rock Springs (The Geysers Geothermal Area) was potentially useful for detecting fracture systems within the steam reservoir, as well as for obtaining other structural-stratigraphic information. Beyer et al. (1976) reported on the value of seismic-reflection profiling for mapping concealed normal faults associated with the Leach Hot Springs Geothermal System, Grass Valley, Nevada. Blakeslee (1984) processed seismic-reflection data obtained by the Comisión Federal de Electricidad over the Cerro Prieto Geothermal Field and was able to define subtle fault features and velocity variations believed to be related to tectonic and hydrothermal effects.

3. Borehole Techniques

Deep boreholes provide the chance to use a wide range of techniques 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 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

Geophysical well logging and log analysis has received a great deal of attention, and some good results in fracture detection have been reported (Suau and Gartner, 1980; Keys, 1984). However, when applied at the high ambient temperatures (> 200°C) found in geothermal wells, geophysical and other wireline devices have failed unless the hole has been precooled with surface waters and the logging is completed rapidly, or unless the tools (electronics, seals, and cables) have been hardened to withstand prolonged exposure to high temperature and corrosive conditions. Few commercial tools work at temperatures above 225°C, and most of them require an uncased well. Table I lists the commercially available logging tools and their rated maximum temperature. Tables IIa and b list the specialized logging tools and their maximum rated temperatures developed by government agencies and their research laboratories. Many of these tools are one-of-a-kind and therefore are not generally available. Table III summarizes the essential features of the common logging techniques for fracture detection in high-temperature environments.

Paillet describes geothermal-well logging tools that are functional to approximately 260°C for 8 hours' operating time (see Table IV) and a logging truck winch that holds 15,000 feet of a 7-conductor cable.

A critical element of any logging tool or borehole and surface-to-borehole technique used in geothermal wells is the signal cable. Table V lists three high-temperature cables that are currently available. Cable with TFE teflon® insulation has been used to 320°C and tested to 350°C by the Los Alamos National Laboratory (LANL) (B. Dennis, personal communication). It is satisfactory for most high-frequency signal applications. LANL transmits a 127-kHz FM carrier signal on their 7-conductor cable. Cables with metal oxide insulation exist and are rated by the manufacturer to 600°C. However, these cables have a high conductor-to-conductor and conductor-to-jacket capacitance that may make them unsuitable for signal transmission above about 1 kHz unless a line driver is used or the cable length is short.

Table I. Commercially available slim-hole logging tools (from The Experiments Panel, 1984).

Tool type	Wellbore	O.D. (in.)	Max. press. (ksi)	Max. 8emp. ($^oF/^oC$)
Schlumberger (Schlumberger Services Catalog, 1978)				
Resistivity				
Induction	Open	2-3/4, 3-7/8	20	350/175
Electrical	Open	3-3/8	25	500/260
Induction spherically-focused	Open	3-1/2	20	350/175
Dual-induction laterlog	Open	3-3/8, 3-7/8	20	350/175
Ultralong spaced electrical	Open	3-5/8	20	350/175
Porosity				
Formation density	Open	2-3/4	25	500/260
	Open	3-3/8	20	400/205
Compensated sonic	Open	1-11/16	16.5	350/150
	Open	3-3/8, 3-5/8	20	350/175
	Open	2-3/4, 3-3/8	25	500/260
Long-space sonic	Open	3-5/8	20	350/175
Compensated neutron	Open	2-3/4	25	500/260
Natural gamma	Open	3-5/8	20	350/175
Temperature				
Temperature	Open	1-11/16	15	350/175
Flowmeter-temperature	Open	1-11/16	20	500/260
Drill string				
Electrical	Through	1-1/2	20	350-500/175-200
Induction	Drill stem	2-3/4	20	350-400/175-205
Sonic	Drill stem	1-11/16	16	300/150
Neutron	Drill stem	2-3/4	25	500/260
Formation density	Drill stem	2-3/4	25	500/260
Gamma ray	Drill stem	2-5/8	25	500/160
Thermal decay	Drill stem	1-11/16	16.5	300/150
Production logging				
Continuous flowmeter	Cased	1-11/16	15	350-600/175-315
Gradiometer	Cased	1-11/16	15	350/175
High-resolution thermometer	Cased	1-11/16	15	350/175
Fluid sampler (650 & 836 cc)	Cased	1-11/16, 2-1/2	10	350/175
Radioactive tracer	Cased	1-11/16	20	275/135

Table I. (Continued)

Tool type	Wellbore	O.D. (in.)	Max. press. (ksi)	Max. temp. (°F/°C)
Logging in Casing				
Gamma ray	Cased	1-11/16, 2, 2-3/8, 3-3/8	20	350-500/175-260
Neutron	Cased	1-11/16, 2, 2-3/8, 3-3/8	12-25	350-500/175-260
Thermal neutron decay	Cased	1-11/16	16.5	300/150
Dresser Atlas				
Electrical				
Induction-electrolog	Open	2	17	350/175
Dual-induction focused	Open	3-5/8	18	350/175
		3-3/8	25	400/204
Dual laterolog	Open	3-5/8	20	400/204
Radioactive				
Compensated neutron	Open	2-3/4, 3-5/8	20	300/150
Gamma-neutron	Open	1-11/16, 3-3/8		
		2-3/4, 3-3/8	17	300/150
Compensated densilog	Open	3	20	300/150
Epithermal neutron	Open	3	20	300/150
Gamma spectra	Open	3-5/8	20	400/204
Acoustic				
Acoustilog	Open	2-3/4	20	450/
		3-3/8, 3-7/8	20	350/175
Production logging				
Nuclear flolog	Cased	1-1/2	12	350/175
Tracerlog	Cased	1-1/2	12	350/175
Fluid density	Open or cased	1-3/4	15	400/204
Temperature	Open or cased	1-1/2, 1-11/16	18	325/163
		1-11/16	17	400/204
Flowmeter	Open or cased	1-11/16, 1-1/8	18	300/150
Fluid sampler	Open	1-11/16	10	300/150

Table IIa. USGS logging tools, January 1982.*

Temperature range (°C)	Log type	Required hole diameter (in.)
100	Sonic ratio (far/near) Sonic delta-t Sonic waveforms Sonic velocity Sonic amplitude	4-1/2 hole; 3" if smooth hole
300	8" resis., normal, uncomp. 16" " " " 32" " " " 64" " " " 8" resis., normal, comp. 32" " " " 64" " " " 8" Wenner induced polarization (IP) 16" Wenner IP 10-cm Dakhnov IP 40-cm Dakhnov IP	3
100	Compensated dual density Density computed from near detector Density computed from far detector Near count rate Far-detector count rate Caliper form density probe	4-1/2; 3 if smooth
300	3-arm caliper	3
100	Neutron count rate Neutron porosity Neutron API units Gamma-ray count rate Gamma-ray API units Equivalent U from gamma ray	3"
80	magnetic susceptibility	4-1/2;

*USGS Branch of Petrophysics and Remote Sensing

Table IIa. (Continued)

Temperature range (°C)	Log type	Required hole diameter (in.)
300	Self potential (single point)	
	Self potential (8" differential)	3
	Self potential (16" differential)	
	Single-point resistance	
	8" differential-resistance	3
	16" differential-resistance temperature	
100	Vertical-component magnetometer	3
	Directional survey	

Table IIb. DOE logging tools.

Tool type	Maximum operating temperature (°C)	Laboratory that developed tool
Temperature	275	Los Alamos National Lab.
Temperature	275	Sandia National Lab.
Temperature	1000	Sandia National Lab.
Caliper	275	Los Alamos National Lab.
Fluid velocity	275	Los Alamos National Lab.
Fluid velocity	275	Sandia National Lab.
Fluid velocity	275	Lawrence Berkeley Lab.
Gamma	275	Los Alamos National Lab.
Geophone	275	Los Alamos National Lab.
Accelerometer acoustic	275	Los Alamos National Lab.
Acoustic detonator	275	Los Alamos National Lab.
Borehole fluid sampler	300	Lawrence Berkeley Lab.
Borehole televiewer	275	Sandia National Lab.
In-situ periodic source	300	Sandia National Lab.

Table III. Borehole geophysical methods for evaluation of fractures in geothermal wells (Keys, 1982).

Type of log	Operational status at 250°C	Fracture Data obtained	Reliability of interpretation	Other considerations
Acoustic televiewer	Unreliable?	Location, apparent width, strike and dip	Very good	Probe must be centralized; heavy mud decreases signal
Acoustic velocity	Unreliable?	Cycle skip at open fractures	Fair	Probe should be centralized
Acoustic waveform	Unreliable	Amplitude anomalies indicate hydraulic aperture	Difficult	Centralized probe--needs digitizing equipment
Resistivity	Reliable	Less resistive anomalies at fractures	Ambiguous	Only short-spaced tools useful
Dipmeter	Unreliable?	Same as above plus fracture orientation	Ambiguous--computer interpretation doubtful	Expensive log
Spontaneous potential	Reliable	Streaming potential; noise at producing fractures	Questionable	Affected by water-quality changes
Temperature	Reliable	Change in gradient at permeable fractures	Very good but semi-quantitative	Some water must be moving in the well
Flowmeter	Unreliable?	Change in flow rate indicates fracture permeability	Needs caliper log; semi-quantitative	Pumping or injecting required
Caliper	Reliable?	Larger hole diameter at fracture	Can be ambiguous	Difficult in deviated wells

Table III. (Continued)

Type of log	Operational status at 250°C	Fracture Data obtained	Reliability of interpretation	Other considerations
Neutron	Reliable	Greater porosity at open fractures	Fair at large fractures	Should be short-spaced and collimated
Gamma-gamma	Reliable	Less bulk density at open fractures	Fair at large fractures	Should be short-spaced and collimated
Gamma and gamma spectral	Reliable	Anomalies at open or closed fractures	Interpretation difficult	

Table IV. Current geothermal logging capabilities, Borehole Geophysics Project, Water Resources Division, USGS.

Tool	Tool diameter (in.)	Remarks
Temperature	2	RTD device
Caliper	2	3-arm
Acoustic	3-1/2	Acoustic velocity and full waveform--operates at 15 kHz
Acoustic televiewer	3-1/2	Operates with 1.3-MHz crystal
Fluid velocity	2-1/2--4-1/2	Spinner type
Natural gamma	2-1/2	NaI crystal
Gamma spectral	3-1/2	1" x 4" NaI crystal
Gamma-gamma	3-1/2	Cs^{137} source
Neutron	2	Am^{241} Be source
Resistance	2	Spontaneous potential and single point
Resistivity	2-1/4	Long (64-in.) and short (16-in.) normal

Table V. High-temperature signal cables for geothermal wells.

Type of Insulation	Maximum temperature (°C)	Number of conductors	Frequency range	Manufacturer
PFA teflon elastomer, armored	260	1-7	dc-100 kHz	Rochester, Vector Cable
TFE teflon elastomer, armored	260 indefinitely, 320-250 for shorter periods	1-7	dc-100 kHz	Rochester, Vector Cable
MgO insulation, stainless jacket, armor-wrapped	600	1, 2, or 4	Basically dc to the kHz range	BICC Pyrotenax

Table VI. High-temperature electronic components (Kelsey and Allen, 1983).

Electronic component	Maximum temperature (°C)	Manufacturer
Operation amplifiers	275	Harris Semiconductor, Inc.
Multiplexer	275	General Electric
Hybrid circuitry for voltage regulators, line drivers, pulse stretchers, and voltage-frequency converters	275	Teledyne-Philbrick

Unless a dewared probe and/or special high temperature electronic components are used, the operating depth and duration of borehole instruments will be severely limited in high-temperature wells (> 250°C). Dewars are commercially available for borehole applications, as are a number of high-temperature electronic components (Palmer, 1978; Veneruso, 1981) (see Table VI). It is not known how much of this technology is being incorporated into the development of higher temperature tools, but silicon CMOS integrated circuits that operate up to 300°C (close to the intrinsic limit for silicon technology) have been tested (Veneruso et al., 1980).

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). Log analysis showed a mean 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.

Well Testing Techniques

Because caliper and standard geophysical logs may not identify the principal fluid-producing fractures, supplementary well testing is often done to distinguish flowing fractures from those that may be sealed by alteration minerals or by 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 6×10^{-8} m^3s^{-1} can be detected in a 50-mm-diameter hole, but the resolution of the technique is reduced by various factors, such as thermal noise arising from small-scale convection and temperature anomalies due to thermal-conductivity variations near the wellbore. Castaneda and Horne (1981) pointed the problem of locating "feed zones" using pressure-temperature logs in shut-in wells when flow occurs between the feed zones.

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 $\sim 8.4 \times 10^{-5}$ 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) has been 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 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 such a water-filled crack is a good reflector of high-frequency electromagnetic and ultrasonic waves, both in-hole Very High Frequency (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 are several technical obstacles that must be addressed. First, there is the deleterious effects of temperature 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 throughgoing 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 an injection well and observation wells (Bodvarsson, 1981; Bodvarsson and Tsang, 1982; Horne, 1982; Pruess and Narasimhan, 1982; Gudmundson, 1984). These techniques sometimes provide consistent information, but there are cases where tracer returns have not agreed with the pressure data. The main problem that arises when attempting to model tracer returns 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 (Achenbach and Viswanathan, 1980; Paulsson and King, 1980; Palmer et al., 1981; King et al., 1984, Fehler and Pearson, 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 both the 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 make the fractures more detectable to electrical methods, one experimenter added brine to the fractures (Chang et al., 1984). To date, most of the geotomographic work has been experimental and limited to holes tens of meters apart. The tools and interpretation techniques have not been extended to geothermal environments. In contrast to the single-hole techniques, the cross-hole sonic and VHF 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 ($\geq$ 10%) may occur, necessitating more complicated analyses accounting for curvature of the ray paths. A problem is to suppress tube wave noise in both source and receiver holes when high energy seismic sources are used.

4. Surface-to-Borehole Techniques

The fourth class of techniques, which we call surface-to-borehole, require a combination of surface and in-hole sources and/or receivers. One of the better known techniques is vertical seismic profiling (VSP), which can be run using both P- and S-wave surface sources (usually mechanical vibrators) at various 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 difficult 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 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 via an existing fracture set, and were not limited to 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 (Chang et al; 1982). Consequently, there has been some interest in developing methodologies to derive fracture-permeability 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.

Surface-to-borehole resistivity measurements have been made for many years (Daniels, 1983). Referred to as the mise-a-la-masse technique, these measurements have generally been used where an electrode could be implanted into a subsurface conductor. By mapping and interpreting surface potentials, one can then obtain a better 3-D picture of the conductor. This approach has been followed 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 the dc resistivity and EM methods. MMR has been shown to be useful for fault mapping (Edwards, 1974). 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 vertical grounded bipole (a pair of current electrodes) in the well and a synchronous magnetic detector, usually 3 components, that maps the field at the surface. A low-frequency transmitter operating near 1 Hz has been used to energize the earth because natural field strength (noise) is low at this frequency. The advantage of the downhole bipole is that the primary magnetic field is zero everywhere at or above the surface of a uniform earth. Thus, measured magnetic fields reflect only current distortions caused by inhomogeneities. For example, a vertical magnetic field is generated if the primary current flow is distorted or channeled by a conductor (Nabighian and Oppliger, 1980; Edwards, 1984; Nabighian et al., 1984. The method is insensitive to topography, but it requires good knowledge of receiver locations. MMR can also be used in the cross-hole configuration (Edwards, 1984; Nabighian et al., 1984), but not in fully cased wells.

Techniques being evaluated for mapping hydrofractures can also be applied to improving the detection of natural fractures. 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 zone 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 have included:

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 an electrode array at the surface (Hart et al., 1983) or the magnetic field changes using surface and borehole magnetometers.
3. Injecting 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 both during injection and after the pumping is stopped (Pearson, 1981; Batra et al., 1984). Arrays of geophones in observation wells can also be used. Encouraging results have been reported at several hot dry rock sites: Fenton Hill, New Mexico (Pearson, 1981), the Carmenellis 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. Shear failure 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 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. Develop improved methods for mappig the length and orientation of hydrofractures.
9. Compare various surface electrical techniques for fault mapping (e.g., head-on resistivity, MMR) by field tests and numerical models.

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APPENDIX A

GEOTHERMAL RESERVOIR DEFINITION: FAULT AND FRACTURE DETECTION AND MAPPING TECHNIQUES

Appendix A. Geothermal reservoir definition: Fault and fracture detection and mapping techniques

Technique	Applications	Resolution	State of Technology	Limitations
1. Remote-sensing techniques				
1.1 Satellite imaging Landsat: multispectral scanner (MSS) thematic mapper (TM)	Mapping topographic variations, vegetation, and various geologic discontinuities that define fault traces or are associated with faults and fluid flow (past and present) along permeable zones. Landsat and SLAR imaging may help define stress directions. SLAR has been particularly useful where heavy vegetation or cloud cover obscure the land surface. Thermal IR scanning has identified thermal contrasts caused by greater moisture content and (sometimes) higher-temperature waters along faults.	30-80 m from satellite heights	Developed technology; data acquisition and interpretation services available from consultants and geoscience-geotechnical groups. Considerable advances have been made in automatic processing and display of data. Better interpretative techniques are available. Work continues to make interpretations more quantitative. The TM will reduce pixel size, hence resolution, to 30 x 30 m. Does not yet have supporting case-history studies to show whether regional and local fault-fracture patterns discerned from air/ground correlate with subsurface fractures in the geothermal reservoir.	1. Nature (cause) of Landsat and SLAR lineaments and discontinuities may not be clear without ground follow-up and/or good geologic maps. 2. Except for Landsat data, data-acquisition costs/area can be very high when techniques are applied to small areas. 3. Does not reveal information on flat-dipping structures. 4. Low-sun-angle photography and SLAR results depend on illumination direction and angle. 5. Landsat imaging has been most effective for mapping "large" geologic structures.
1.2 Aircraft imaging Low-sun-angle black and white Color and false-color infrared (CIR) Side-look radar (SLAR) Thermal infrared (IR) scanner		$\leq$ 1 m from aircraft heights		

Technique	Applications	Resolution	State of Technology	Limitations
2. <u>Surface techniques</u>				
2.1 <u>Geologic mapping</u>	Mapping of fault-fracture-joint sets in outcrop area. Applied in conjunction with airborne and satellite imaging. May be able to define open vs. sealed fractures, measure apertures, and define age relationships between stages of fracture openings.	mm	Developed technology in common use. Limited experience at several geothermal fields indicates that open fractures are present near the crests of anticlinal folds or in horst blocks (i.e., where theory would predict extensional horizontal stresses).	1. Question of whether surface data can be extrapolated to reservoir depths. 2. Requires a large outcrop area for a statistically reliable data set. 3. Not easy to predict apertures of fractures at depth. 4. Fracture length subject to truncation biases.
2.2 <u>Geochemistry</u> Volatile elements and gases (Rn, He, Hg) Nonvolatile elements (e.g., As, Bi)	Trace-element analyses of soils and soil gases (sometimes rocks) as clues to the trace of convective flow paths.	1-10 m, but depends on sampling interval.	Largely developed; techniques are used in oil, mineral, and geothermal exploration. Case-history base for geothermal areas is small but growing. Used with geologic mapping and airborne imaging. May be diagnostic in areas of limited outcrop.	1. Indicates main discharge areas. 2. Anomalies may be too diffuse to resolve conduits other than their general location and orientation. 3. Nonvolatile elements may indicate fossil (and possibly sealed) conduits.

Technique	Applications	Resolution	State of Technology	Limitations
2. Surface techniques (continued)				
2.3 Geophysics				
2.3.1 Nonseismic geophysics				
Gravity	Gravity and magnetics are used to map vertical and dipping discontinuities that may be fault-related features.	10^2-10^3 km+	Gravity and magnetics are standard techniques in common use by geophysicists for obtaining subsurface structural information. They are an adjunct to geological methods; they do not depend on outcrop, but they must be used with an integrated geophysical-geological methodology (Pálmasson, 1976; Flövenz and Georgsson, 1982).	Gravity and magnetic results may be geologically ambiguous, and nonunique.
Magnetics	Paths of high fluid permeability may parallel dikes that can be detected magnetically.			
Self Potential (SP)	SP (electrical) anomalies sometimes correlate with geothermal fields and surface manifestations. SP results can sometimes be modeled and explained in terms of flow along faults.			SP anomalies can arise from a number of causes unrelated to fractures and fracture flow.

Technique	Applications	Resolution	State of Technology	Limitations
2. Surface techniques (continued)				
2.3 Geophysics (continued)				
2.3.1 Nonseismic geophysics (continued)				
Electrical - electromagnetic	Long linear zones of low resistivity may be related to shear or fault zones in basement rocks and associated geothermal water. Resistivity anisotropy may indicate either relative ease of current flow in the dominant fracture direction or channeling of the current into a discrete fracture zone. For example, "circular vertical electric soundings" (CVES) may indicate preferred fracture directions in basement rocks (Stagalino et al., 1982).	Depends strongly on both the depth-to-width ratio and the resistivity contrast between host rocks and fracture zone.	Many electrical and electromagnetic methods in routine use have provided information on faults. Experimental electrical techniques based on the quadripole Schlumberger sounding may resolve conductivity anisotropy at depth, hence the predominant directions of fractures in basement. This is a new method, little used in the USA. (Stagalino et al., 1982). Head-on resistivity profiling is commonly used in Iceland for detecting near-surface subvertical fractures (Flövenz, 1984). Magnetometric resistivity (MMR) also reported useful for fracture detection (Edwards, 1974).	Many electrical-electromagnetic techniques respond extremely well to narrow subvertical conductors that come close to the surface. Results are usually difficult to interpret in a rigorous geological fashion. The presence or absence of an anomaly in conjunction with other information is often the chief diagnostic sought.

Technique	Applications	Resolution	State of Technology	Limitations
2. Surface techniques (continued)				
2.3 Geophysics (continued)				
2.3.1 Nonseismic geophysics (continued)				
Surface deformation geodetic surveys	Present directions and rates of surface deformation due to tectonic processes may provide an indirect guide to orientation of extensional fractures.	Unknown	Experimental	This technique is probably best applied in association with other geological and geophysical measurements and observations.
2.3.2 Seismic techniques				
Passive seismic, microearthquake monitoring (MEQ)	Involves the detection and location of microearthquakes that are presumed to be related to small movements on active faults.	~ 100–200 m, but depends on knowledge of the velocity section.	Tight arrays of geophones and in-field automatic detection, location, and display are used (McEvilly and Majer, 1982). Technology for data acquisition and processing is now fairly standard (Majer, 1978). MEQ has been used successfully in some geothermal areas for exploration (Combs and Rotstein, 1976).	1. Swarm activity along active faults is unpredictable, necessitating long monitoring times. 2. Not all geothermal areas will have natural seismic activity within the reservoir region.

Technique	Applications	Resolution	State of Technology	Limitations
2. Surface techniques (continued)				
2.3 Geophysics (continued)				
2.3.2 Seismic techniques (continued) High-resolution seismic reflection and refraction	Applications to geothermal exploration and reservoir delineation have been confined mainly to basinal, sedimentary environments. Major faults detected are in good agreement with well logs and other geophysical interpretations. Combined seismic reflection and detailed gravity worked well in the Basin and Range Province. Reflection well-suited to flat or nearly flat discontinuities. Seismic velocities controlled by the total fracture porosity in the direction of seismic-wave propagation. Velocity anisotropy may provide information on orientation of open fractures.	High-resolution, multifold common depth point seismic reflection and imaging can resolve vertical and horizontal discontinuities $\leq$ 100 m. The resolution depends on many variables, e.g., depth to and reflectivity of discontinuity, source characteristics.	Few surveys have been run in geothermal areas (Denlinger and Kovach, 1981; Blakeslee, 1984), but the basic technology is well worked out (Mair and Green, 1981; Hajnal et al., 1983). Considerable research completed and in progress on how fractures and pore fluids modify the physical parameters of rocks. Most of this work has been on small-scale rock samples. Results not extrapolated to *in situ* conditions and large rock volumes. Use of both P- and S-wave vibrators makes it possible to measure variations in V_P, V_S, and V_P/V_S, as well as measure energy attenuation in P- and S-waves. 3-D processing of seismic data has provided a great deal of information on conjugate sets of steeply dipping faults within the Austin Chalk (Calcote et al., 1982).	1. Strong horizontal and vertical gradients in velocity make it difficult to image data accurately. 2. May not be able to distinguish a zone of fractured rock from one that may be intensely hydrothermally altered. 3. Limited to areas where it is possible to get energy into the ground; e.g., technique may not work in some volcanic covered areas.

Technique	Applications	Resolution	State of Technology	Limitations
3. Borehole techniques				
3.1. Single Hole, Wireline Logs Methods applied usually as a suite and studied in relation to driller's logs, mud logs, and geological logs and core samples. Pressure-temperature profiles Spinner surveys Caliper logs Sonic-velocity logs Fracture identification log (FIL$^{\text{tm}}$) Impression packer Borehole television (video) Acoustic borehole televiewer (ABT) Natural gamma ray Circumferential propagating seismic logs	Maps and characterizes single and multiple fracture sets intersected by wellbore. Faults can be recognized from logs; e.g., change of dip of marker beds, absence or repetition of marker beds. Faults and fractures containing flowing waters can be recognized by perturbations in temperature-pressure-spinner (flowmeter) profiles. Zones of fractured rock can be recognized and inferred from a combination of standard geophysical well logs that respond to variations in density, resistivity (induced log and resistivity dipmeter), and sonic velocity, all of which are related to, but not specific to, the presence of fractures (Morris et al., 1964; Zemack et al., 1969; Myung, 1976; McCoy et al., 1980; Suau and Gartner, 1980; Hirsch et al., 1981; Keys, 1982; Nelson, 1982; Timur, 1982; Moos, 1983; Kleinberg et al., 1984).	Can resolve fractures with apertures in the mm range. Can resolve fracture orientation to ± 2° using the the ABT.	Technology developed for and in use by oil/gas industry where high subsurface temperatures are not a problem except in a few areas. A variety of slim-hole tools for higher temperature environments available (see tables II, IIIa, IIIb, V). Major R&D efforts needed to harden electronics, seals, and cables for prolonged use under high-temperature and corrosive geothermal wellbore conditions. Some tools such as the ABT have been successfully tested to 250°C and 5000 psi after modifications to existing hardware. Other tools have reported operational to 260°C for 8 hours (see Table V). Work on high-temperature elastomers used as seals and insulators has resulted in cable heads that can operate in the 250-300°C range. Multiple-conductor high-temperature cable (300°C) is commercially available (see Table VI).	1. Commercial wireline methods have an upper temperature limit of 175-225°C. 2. Questions of reliability of tools and techniques for discerning fractures. 3. All borehole techniques except pressure/temperature and radiometric log require an uncased hole. 4. Borehole television and ABT require clear water in wellbore. 5. Some logs, such as caliper, sonic-velocity FIL, and impression packer may respond to wellbore roughness and washout zones caused by formational effects. 6. Logs such as sonic velocity, resistivity, porosity, and formation density provide only indirect information and must be interpreted with other information. 7. Cannot determine fracture length; apertures poorly defined. 8. Few logs provide dip-and-strike information.

Technique	Applications	Resolution	State of Technology	Limitations
3. Borehole techniques (continued)				
3.1 Single-hole wireline logs (continued)	Borehole gamma spectrometry used to identify anomalous concentrations of U, Th, and K associated with circulation of hydrothermal fluids along fractures (Keys and Sullivan, 1979).			
3.2 Single hole, geologic, hydrologic - reservoir testing				
3.2.1 Core logging	Zones of particular interest for detailed study are drilled by means of a special core barrel and diamond drill. Either oriented or (more commonly) unoriented cores are recovered.	High	Technology well developed. Strike-dip of fractures in cores have been determined by magnetic measurements (Hayashi and Furutani, 1982).	1. Core recovery is very low in badly fractured rock. 2. Sometimes hard to distinguish major from minor fractures and natural from mechanical fractures.
3.2.2 Mud logs	Mud losses during drilling are carefully monitored and give fairly accurate information on location of permeable zones.	Depth to fracture zone resolved to within ± 2 ft	Standard technology. Data not too diagnostic alone. Usually supported by rate of drill penetration and wireline logs.	Data informative but not too diagnostic alone.

Technique	Applications	Resolution	State of Technology	Limitations
3. Borehole techniques (continued)				
3.2 Single-hole, geologic, hydrologic - reservoir testing (continued)				
3.2.3 Tidal strain - pressure response	The measured fluid pressure response to solid earth tides contains information on the nature of formation deformation, including fracture orientation and reservoir structure. Data acquisition involves taking shut-in static-well pressure record. Wells having a positive wellhead pressure can be monitored at the surface. The phase shift between pressure and tidal potential is a function of the principal orientation of fractures communicating with the well.	Results indicate orientation of subvertical fracture sets to ± 10° (90% confidence limits).	Technique has had limited use. Technique is considered experimental, but good results have been reported (Hanson and Owen, 1982).	1. Fractures must have large permeability. 2. Technique must resolve pressure signals as small as 10^{-3} psi (i.e., high-resolution quartz pressure transducers are required). 3. A few weeks of data acquisition are needed.

Technique	Applications	Resolution	State of Technology	Limitations
3. <u>Borehole techniques</u> (continued)				
3.2 <u>Single-hole, geologic, hydrologic - reservoir testing</u> (continued)				
3.2.4 Stress measurements (Hydrofracturing tilt measurements)	Hydrofracturing of low-permeability rocks can obtain direction and magnitude of least principal stress. From this one can infer the dominant fracture direction. Surface arrays of tiltmeters and downhole logs have been used to determine fracture direction.	Resolution depends in part on ability to map orientation of the hydrofrac.	The hydraulic fracturing technique is reasonably well developed for both low- and high-temperature environments (to 250°C). However, the accurate determination of hydrofrac orientation is not always easy (see Sec. 4.3).	1. Stress is an indirect method of inferring the orientation of natural fractures. 2. The fracture orientation can be determined by a combination of wireline logs (see Sec. 3.1), interpreted tiltmeter data, and/or monitoring the fluid injection (see Sec. 4.3). 3. Tiltmeters are difficult to interpret for the following reasons: o Signal processing must remove effects of earth tides and diurnal heating. o Background-noise data must be obtained over many days spanning the injection. o The theoretical depth of investigation is about 10^3 ft; in practice it may be far less.

Technique	Applications	Resolution	State of Technology	Limitations
3. <u>Borehole techniques</u> (continued)				
3.2 <u>Single-hole, geologic, hydrologic - reservoir testing</u> (continued)				
3.2.5 Injection/production tests	Injection/production tests are made in well, with the zone of interest isolated using single or double packers.	May be able to determine the hydraulic properties of the fractures and distinguish between vertical and horizontal fracture zones. Without other downhole data (e.g., wireline logs), only general inferences can be made about the aperture and orientation of fractures.	Technology well developed, especially with regard to hydraulic fractures (Pine, 1983; Ramey and Gringarten, 1982). Considerable advances have been made in wellhead and downhole instrumentation, automatic data processing/data display, and interpretative techniques.	1. High-temperature packers needed. 2. Does not give information on individual fractures.
3.3 <u>Single-hole, downhole geophysical methods</u>				
Very low-frequency (VLF) - electromagnetics (EM)	Natural or manmade VLF signals in the 12-20 kHz range are the signal sources. As these normally have no vertical electric field in the earth, anomalous conditions are detected by profiling a well using a pair of downhole electrodes and appropriate electronics.	Reported to be sensitive to nonhorizontal conductive fractures intersecting wellbore.	Tested numerically and in the field (Becker, personal communication).	VLF signal amplitude attenuates in conductive earth. This technique is generally limited to depths <500 m and to uncased wells.

Technique	Applications	Resolution	State of Technology	Limitations
3. Borehole techniques (continued)				
3.3 Single-hole downhole geophysical methods (continued)				
Very high-frequency (VHF) pulse radar with directional antenna	Detects and determines orientation of a nearby fluid-filled fracture not intersected by the wellbore by back-scattered energy (30-100 MHz). Technique is analogous to reflection seismology turned on end and with source-receiver in a borehole.	Depends strongly on the fracture aperture, continuity, distance from wellbore, and nature of fluid in the fracture. Fluid-filled fractures in granite with apertures of ~ 1 mm are theoretically detectable (Hartenbaum and Rawson, 1980).	Experimental; some prototypes built and tested; not much commercial interest yet. Experimental problems encountered: omnidirectional antennas produce clutter from various geologic reflectors, and it is hard to pick out and intepret the returned signal from the fractures.	1. Ambiguous results due in part to geologic noise sources (scatters). 2. Detection range is probably small (< 25 m), possibly less in conductive geothermal environments. 3. No equipment available for high-temperature corrosive environments. 4. Developing a highly directional and steerable borehole VHF antenna is difficult.
In-hole seismic-reflection ultrasonic reflection	Acoustic signals are created and detected by an in-hole instrument. The reflection P and SH waves from a fluid-filled crack near the borehole are sought. The technique is similar in concept to VHF pulse radar except that ultrasonic-frequency acoustic-wave energy is generated and detected.	Same as above.	A number of ultrasonic seismic-reflection systems have been built and tested at granite quarry sites or in the laboratory (Yu and Telford, 1973; Hartenbaum and Rawson, 1980; Palmer, 1982; Chang et al., 1984).	1. Requires an exceptionally reflective layer or surface. 2. Data may be difficult to interpret; clutter exists from multiple scatterers.

Technique	Applications	Resolution	State of Technology	Limitations
3. Borehole techniques (continued)				
3.4 Multiple-hole or cross-hole methods				
3.4.1 Geophysics				
Cross-hole acoustic tomography	Maps the variation in the P- and S-wave velocities and/or attenuation of ultrasonic waves (10-100 kHz) in the region between two or more wells.	Can resolve anomalous zones on the order of <1 m. Actual resolution depends on borehole separations, number of sources and receivers, separation between the transmitter-receiver points, and frequencies used.	Experimental work done but not used commercially (McCann et al., 1975; Paulsson and King, 1980; Wong et al., 1983; Rezowalli et al., 1984).	1. Wells must be relatively close together ($\leq$ 200 ft) to measure the small signals. 2. High temperatures in geothermal wells limit electronics.

Technique	Applications	Resolution	State of Technology	Limitations
3. Borehole techniques (continued)				
3.4 Multiple-hole or cross-hole methods				
3.4.1 Geophysics (continued)				
Cross-hole VHF pulse radar (radar tomography)	Maps the variations in EM energy transmitted in the region between two or more wells. To improve conductivity contact, salt water was injected into the fracture network around one hole. The signal loss due to the highly attenuating fluid-filled fractures was detected by receivers in adjacent holes (Ramirez et al., 1982). Differences in attenuation prior to and after saltwater injection indicated the location of permeable zones. Results compared well with geophysical logs.	Same as above.	Largely experimental; not developed yet for geothermal environment.	1. The highly conductive nature of the geothermal environment could improve the serious limitations on the effective range of the techniques (i.e., small well separations). 2. Geotomographic interpretations usually assume that the EM waves travel along straight paths between transmitter and receiver. This condition is satisfied when displacement currents dominate over conduction currents (i.e., the wavelength in rock is much smaller than the skin depth of the medium) and when velocities in the medium are constant.

Technique	Applications	Resolution	State of Technology	Limitations
3. Borehole techniques (continued)				
3.4 Multiple-hole or cross-hole methods (continued)				
3.4.2 Geology				
Multi-hole geologic correlations from driller's lithologic geophysical well logs	May be used to map fault zones and/or zones of fluid movement. Used in conjunction with temperature and spinner survey results.	Major dip-slip faults should be identifiable.	Conventional geologic technology made more diagnostic when used with temperature-spinner profiles in wells and other geophysical well logs.	Holes must must be close-spaced to distinguish faults from other structures.
3.4.3 Geochemistry				
Tracer tests	Rate of return of nonreactive tracers between multiple observation wells gives some indication of where permeable zones are.	Technique does not resolve individual fractures; if only indicates preferential flow-path directions.	Nonreactive tracers are used in geothermal reservoir studies; tracer breakthrough times at observation wells permit one to construct a fracture model (Vetter and Zinnow, 1981). Tracer research needed.	1. Does not resolve individual fractures. 2. Results sometimes difficult to interpret and nonunique. 3. Nonradioactive tracers often interact with rock: adsorption, ion exchange, etc. 4. Tracer returns sometimes do not agree with pressure-interference test data between wells (Horne, 1984, personal communication).

Technique	Applications	Resolution	State of Technology	Limitations
3. Borehole techniques (continued)				
3.4 Multiple-hole or cross-hole methods (continued)				
3.4.4 Hydrology				
Cross-hole or multiple-hole interference tests	The pressure response in one or more observation wells is measured as fluid is either extracted from or injected into the test well.	Unless care is exerted to pack off specific zones and the wells are closely spaced, the technique does not resolve the hydraulic characteristics of individual fractures.	Technology is well developed for porous media; less well developed for fractured rocks.	1. Results difficult to interpret and non-unique with respect to flow paths. 2. Multiple-hole tracer tests sometimes give contradictory results that cannot be explained by porous-media or simple-fracture models.

Technique	Applications	Resolution	State of Technology	Limitations
4. Surface-to-borehole techniques				
4.1 Seismic				
Vertical seismic profiling (VSP)	Uses surface P- and S-wave vibrators at varying offsets and azimuths from the well. A single 3-component geophone or a string of geophones are placed in well to find evidence for major fractures near or intersecting the well.	100 m	VSP is in common use by the oil and gas industry, but it does not yet appear to have been applied in geothermal areas (Gal'perin, 1973; Balch et al., 1982). Both P- and S-wave vibrators are available. Several commercial conductors offer VSP surveys. A hydrofrac was detected and delineated by S-wave VSP. An S-wave shadow zone was found after hydrofrac operations (Fehler et al., 1982). Used in conjunction with surface seismic-reflection, wireline sonic velocity, and other geophysical logs.	1. Positive identification of the hydrofrac is required both before and after VSP and conventional (nonseismic) borehole methods. 2. The fractured region must be a few wavelengths in height and length to cause the shadow; thus only massive zones of fractured rock will cause an S-wave shadow.

Technique	Applications	Resolution	State of Technology	Limitations
4. Surface-to-borehole techniques (continued)				
4.1 Seismic (continued)				
Tube-wave excitation (related to VSP)	Surface P- and S-wave sources create pulses that, when they impinge on a horizontal fracture intersecting the borehole, squeeze the fracture, thereby injecting fluid into the well and exciting tube waves (Stonley waves) in the wellbore. Presumably, the fracture location can be determined from amplitude information.	Not yet known.	Theoretically, the ratio of fracture-induced tube waves to the incident P-wave amplitudes can be interpreted in terms of a "fracture permeability" (Beydoun et al., 1983). Technique is at an early stage of evaluation.	1. Experimental techniques require an open hole and an independent determination of V_P and V_S of the host rock. 2. Tube waves may also be excited if the source too close to the well, i.e., if surface waves are converted into tube waves.
4.2 Electrical and electromagnetic (EM) methods				
Surface-to-downhole EM	A large EM transmitter is placed at the surface near the well, and a single or three-component detector is run into the well. Maps condition of rock around well. May provide useful information in cased wells. Gives information on rocks below bottom of well.	Not yet determined.	Early-stage experimental.	1. In-hole detector not yet built and tested for geothermal environment. 2. Theoretical assessment of technique is in progress.

Technique	Applications	Resolution	State of Technology	Limitations
4. <u>Surface-to-borehole techniques</u> (continued)				
4.2 <u>Electrical and electromagnetic (EM) methods</u> (continued)				
Surface-to-downhole resistivity	"Mise-a-la-masse" techniques are used, in which a downhole current electrode is placed into a conductor and surface potentials are mapped to obtain better definition of the conductor is direction and shape. A related approach is magnetometric resistivity (MMR), in which current channeling is sought from surface magnetic-field measurements.	Not yet determined.	Surface-to-borehole dc resistivity has been used in at least two wells to map a subsurface conductor (Kauahikaua et al., 1980; Tamagori et al., 1984). The well casing can sometimes be used as the downhole electrode. In an uncased well the MMR approach may be promising but has not yet been applied to a geothermal situation.	Not yet known, but interpretation is probably difficult when multiple conductors are present.

Technique	Applications	Resolution	State of Technology	Limitations
4. Surface-to-borehole techniques (continued)				
4.3 Fluid-injection monitoring	A fracture zone is mapped by injecting a special fluid or fluid-proppant mixture into a fracture and monitoring the "disturbance" by (a) self-potential, (b) electrical/ electromagnetic, (c) magnetic, or (d) seismic detectors at the surface or in observation wells.	Not yet determined.	Seismic monitoring has been done at various experimental scales in cold and hot environments (Pearson, 1981; Batchelor et al., 1983; Majer and Doe, 1984). Experiments to detect magnetic proppants in fractures are in progress. Self potential may have promise. Sandia (Hart et al., 1983) reports success in mapping distortions in electrical potentials around a well where acid was pumped into hydrofractures at 4000 ft. The well casing was energized by a low-frequency current source to couple the current into the conductive frac fluid (mise-a-la-masse).	1. Not yet known, but some research is in progress to determine limits of detection/resolution and types of fluids needed. 2. More numerical evaluations are needed to evaluate potential techniques and to analyze existing data.