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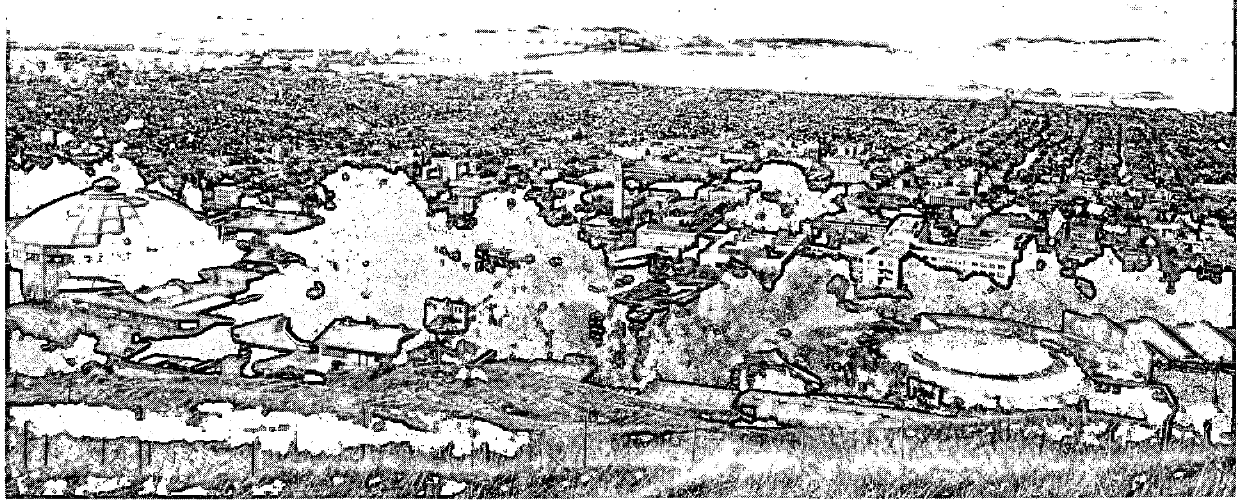

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FRACTURE DETECTION AND MAPPING

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Abstract

Because the costs of drilling, completing, and testing a well can be extremely high, it is important to develop better tools and methods for locating high permeability zones prior to drilling, and to develop better tools and methods for identifying and characterizing major fracture zones during the drilling and well testing stages. At the recommendation of the LBL Industry Review Panel on Geothermal Reservoir Technology, we organized and convened a one-day workshop this past July to discuss various aspects of DOE's current and planned activities in fracture detection, to review the geothermal industry's near-term and long-term research needs, to determine the priority of those needs, to disseminate to industry the status of research in progress, and to discuss the possibility of future joint research between industry and DOE. In this paper we present a brief overview of the workshop from the perspective of those who participated in it and provided us with written comments to a questionnaire that was distributed.

INTRODUCTION

In March 1985, the LBL Industry Review Panel on Geothermal Reservoir Technology, discussed last year by Gulati and Lippmann (1985), reconvened to review the status of the DOE Geothermal Technology Division's (DOE/GTD) Reservoir Technology Program. Among the Panel's recommendations was that DOE contractors and industry organize and hold a number of informal one-day workshops on specific topics as a timely way of transferring information on current research being sponsored by DOE/GTD. The authors were asked to organize and convene a workshop on fracture detection and mapping.

The informal workshop, held on 11 July 1985, was attended by around 30 invited scientists and engineers from geothermal companies, consulting and service organizations, DOE/GTD program managers, and DOE contractors (Table 1). Representatives from the different research groups gave brief reports on their work. As is usually the case, some of the invited speakers were unable to attend, and so we were unable to discuss the full range of topics being studied through the auspices of DOE and the USGS. Due to the limited time available, however, it would have been virtually impossible to cover everything properly had everyone attended. We also managed to bring to the workshop speakers whose work is not funded by DOE, but whose expertise is germane to the subject. The workshop agenda is shown in Table 2. Goldstein and Cox (1985) compiled an informal summary report that has been distributed only to the workshop participants, but copies are available through the Earth Sciences Division of LBL.

At the end of the workshop an hour was devoted to general discussions. One of us (JLI) distributed a prepared questionnaire asking the attendees to respond in writing to five questions:

(1) What do you consider the principal research areas? Please prioritize.

(2) What areas of current research should be expanded or contracted? Please explain.

(3) What additional areas of research, not currently being conducted, should be undertaken?

(4) What do you consider potentially viable areas for joint efforts by industry and DOE?

(5) Do you feel that a more in-depth workshop, lasting approximately two days, on selected topics is warranted? If so, what topics should be discussed?

Because only 11 written responses were returned we could not prioritize research needs. Nevertheless, we summarize here some of the key points made to the questionnaire and expressed during the workshop.

PRINCIPAL RESEARCH DIRECTIONS

Opinions expressed in answer to questions 1,2,and 3 usually reflected the individual's background and experiences. The remarks seemed to fall into three major areas of concern:

(1) locating fractures and zones of high permeability *prior* to drilling,

(2) identifying the major permeable zones *during* drilling, and

(3) developing better physical and conceptual models for fractured geothermal reservoirs.

Not mentioned in the questionnaire responses or brought up during the workshop is the topic dealing with the relationship between fracture permeability and large-scale or dominant fluid flow paths within the reservoir region. However, this topic is touched upon in the following discussions.

DISCUSSION

Locating Fractures and Zones of High Permeability Prior to Drilling

Where fluid flow is controlled primarily by fractures, it is vital to target wells to intersect fractures that are well connected and which drain a large volume of rock. This may require an understanding of the nature and controls of fracturing, and which fractures or fracture sets have the major control over fluid flow at reservoir depths.

a. Detailed geological mapping of faults, fracture and joint traces, and volcanogenic features on the ground, supported by air photos, LANDSAT and other airborne imagery, is considered basic to understanding the deformation history of a region. Brought out at the workshop was the point that major lineaments and arcuate traces seen on air photos are quite often related to permeable zones, some of which persist to depth. On the basis of historical water well records, the chances of encountering good aquifers are measurably better for wells sited on or near these features and their intersections. However, surface features may not always extrapolate to reservoir depths. For example, observable rocks may be allochthonous, and/or may have experienced a different cooling and tectonic stress history from those at depth. Some of the uncertainties might be worked out if one had a reasonably accurate model for the thermal/tectonic evolution of the area. In fact, clay-box analog models are still used to develop fracture concepts for structurally complex terranes where elastic theory alone does not suffice.

b. The workshop did not include discussions of geochemical techniques, but references were made to geochemistry in the written responses by several who favor more geochemical research. One area of study related to permeable zones involves the study of certain soil gases (H, ^{3}He, ^{222}Rn, and various noble gases) as indicators of migration paths. On the basis of the current literature a considerable amount of study is being directed to soil-gas anomalies, which the authors often associate with seismic activity, fractured rocks, and the storage and release of volatiles from crustal or mantle sources.

c. Further advances in the use of surface geophysical techniques for fracture mapping are possible. While it is still debated whether geothermal systems emit measurable seismic energy due to thermal stress cracking, many geothermal fields are reported to have higher levels of seismic noise. Most occur in tectonically active areas where the detailed study of the seismicity may provide information on the location and style of brittle deformation, including the deviatoric stress directions. Lew Katz discussed the correlation between seismic emission anomalies and several geothermal areas in Nevada, pointing out that emission anomalies often correlate with known cross faults (Katz, 1984). In contrast, The Geysers field shows unusual seismic behavior. Previously aseismic areas within the steam field have become active after production commences, failure occurring on randomly oriented and distributed faults that are uncorrelated to mapped faults (Oppenheimer, 1985).

High attenuation of seismic waves has also been noted at major fault intersections, and there is growing evidence that stress-aligned, water-filled microcracks are the cause of seismic anisotropy. This feature is observed as the splitting of shear waves into components with different polarizations and different group velocities (Crampin, 1978). Some of the best evidence for this effect has come from Vertical Seismic Profiling (VSP) in wells using a clamped 3-component borehole geophone and directional shear-wave sources at the surface. Majer et al.(1985) have used this approach to determine the dominant direction of fractures at The Geysers geothermal field with apparent success.

An alignment of water-filled fractures should also produce an electrical anisotropy. Where observed at geothermal fields, electrical anisotropy has been explained as the effect of stronger ionic conduction in the direction of the dominant open fractures (Stagalino et al., 1982). Interestingly, concurrent investigations of both electrical and seismic anisotropy have not yet been carried out in a fracture dominated environment to see how well both parameters agree, and whether they correctly indicate the principal flow direction.

One of the simpler and more interesting geophysical methods for detecting fluid flow in major fractures is self-potential. Several workshop attendees endorsed further studies related to the electrokinetic SP effect, including more SP surveys at thermal and non-thermal areas.

It was generally agreed that conventional surface geophysics (active seismic, gravity, and electrical-electromagnetic) is capable of resolving many major fault zones (macrofractures), but the same techniques would not resolve discrete fracture zones at reservoir depths due to the small target dimensions, and interference from surface and deeper sources of geologic noise. Individual, subhorizontal permeable zones such as cataclastic rocks (e.g.,tectonic breccias), rubbly flow tops, and well-jointed flows would be hard to detect unless the zones were thick, continuous, and shallow. Subvertical to vertical permeable zones such as breccia pipes and fractured zones at intersecting faults would also be undetectable unless they approach the surface or have a small depth-to-diameter ratio.

d. Detailed case studies of fractured geothermal systems, including fossil hydrothermal systems, are considered very important for characterizing the type(s) of fracture system(s) and for understanding the interrelationships between fracture parameters and hydraulic processes. Case study reports are appearing for studies made in the U.S., Canada, Sweden, and other countries that are evaluating sites for the geologic disposal of nuclear waste. Some of the information may be directly applicable to geothermal systems, but there are enough basic geologic differences that the waste-site studies will not supplant case studies of fractured geothermal hydrothermal systems. Presently, the only fractured reservoir for which there is adequate published information is the Redondo Creek area of the Valles Caldera, New Mexico, discussed by Dennis Nielson at the workshop.

Case studies must have complete geologic, geochemical and geophysical information, including the signatures of upflow and discharge zones. Geochemical studies of veins and fracture minerals may provide information on the time-temperature-pressure history of the flow system. Geologic studies are needed to determine the age of the fractures and their relation to the mechanical and thermal stress history of the area.

Identification and Location of Major Permeable Zones During Drilling

Under certain drilling situations identification of major permeable zones has not been straightforward. Properly locating such zones during drilling can be critical to, among other things, setting of production casing, avoiding wasteful and futile attempts to test production from the wrong zone, and deciding whether a hole should be completed. Because most holes are drilled vertically they are not optimally oriented to intersect open fractures, most of which are likely to be subvertical to vertical at reservoir depths. It would be desirable to have tools and methods to detect a nearby fracture zone so that a deviated wellbore leg can be drilled while the rig is still on the hole.

a. Only slight mention of well-logging techniques was made at the workshop. It is fairly common knowledge that these techniques have been evaluated for fracture detection under controlled test conditions at a number of crystalline rock sites (Paillet, 1981; Hearst and Nelson, 1985; Jones et al., 1985, among others). The multi-arm caliper, borehole televiewer (BHT) and other acoustic tools, the dipmeter and other resistivity tools, and the neutron (porosity) log are all effective for locating fractures. The BHT and dipmeter give fracture orientation. No log has been conclusively shown to be effective for aperture or hydraulic parameters, and only the BHT will resolve vertical fractures (Paillet, 1981). Because the most interesting fractures admit hot fluids into the wellbore, a combination of self-potential, temperature, and spinner logs (the latter if the well can be made to flow) are considered very valuable. To this list one might add natural γ-ray if the circulating groundwater picked up trace amounts of Rn.

The problems and practical limitations of borehole logging in geothermal environments have been discussed in the recent literature by several authors. One such case study, presented by Al Waibel at the workshop, dealt with a layered volcanic sequence for which there was very poor correlation between the various techniques that one uses to identify fractures and fluid entries. Lost circulation zones were encountered in lava flows, sills or dikes, and welded tuffs. However, none of these zones were indicated on temperature profiles or on other geophysical logs.

In spite of these problems, borehole logs are an important component of any field case study, and the development and testing of improved tools to withstand temperatures higher than 200 to 250°C needs to be continued. Distinct from determining fracture location, density and orientation, the estimation of hydraulic parameters of individual fractures or fracture zones from well logs has also received serious attention. The results have usually been disappointing. However, in a field test at a non-thermal area a linear relation was found between neutron log response and the logarithm of hydraulic conductivity for the fractured granite (Jones et al.,1985).

b. An estimate of hydraulic conductivity or permeability of a specific interval in a hole is commonly done by means of pressure tests using a single-hole straddle-packer and/or drillstem device. The limitations with these methods are that the results pertain only to the immediate vicinity of the borehole, and in a direction more or less perpendicular to the hole (Hsieh et al., 1983). Moreover, conventional pressure transient methods suffer from problems of non-uniqueness of the pressure decay curves when multiple fractures with variable apertures and lengths intersect the hole and the need for high resolution of early time data. Discussions were held at the workshop on some novel approaches being studied. Sally Benson talked about nonisothermal well testing, thermal front tracking, and turbulent flow analysis. Paul Kasameyer described the tidal strain technique for obtaining the dominant direction of fractures intersecting the borehole (Hanson and Owen, 1982).

c. Surface-to-borehole geophysics has some promising aspects. The workshop attendees were particularly impressed by the VSP approach, and also thought that the tidal strain and electrical methods, as described by Craig Beasley (Beasley and Ward, 1985), might have application. Among the surface-to-borehole geophysical methods one might also include seismic monitoring during a large-volume hydrofracture. Leigh House described one such study conducted at Fenton Hill where the cloud of induced microearthquakes mapped the path of fluid invasion.

d. Although electromagnetic(EM) and acoustic borehole and crosshole techniques are being evaluated for their ability to detect a major proximal fracture not intersected by the hole, there remain a number of engineering problems regarding transmitter design and signal recognition. Pulsed acoustic and EM sources that are directional, steerable, and will work in the confines of a well have been designed and tested to a limited degree, but not to the extent of commercialization and not for use in geothermal environments.

e. A few replies mentioned the need for additional studies of geochemical, mineralogic, and physical property variations encountered in geothermal systems. This information is needed to calibrate and interpret information from surface and borehole investigations, and to understand the past and present temperatures, pressures, and water-rock reactions. The best studied geothermal systems exhibit zonation in major and trace element geochemistry, mineralogy, and physical properties that are mainly a function of temperature, hydrothermal circulation and chemical reactions, boiling, and the mixing of non-thermal waters. It should be possible to reconstruct from the zonation patterns a picture of the fluid circulation system, resolving zones of upflow, mixing, and discharge.

f. Although a discussion of geochemical tracers was not presented at the workshop, two respondents felt that multi-well tests, that include the use of tracers, was needed to study the dominant flow paths in deep (7,000 to 10,000 feet) fractured reservoirs. Tracers will be covered during the one-day workshop on "Chemical Aspects of Injection", scheduled for 24 January 1986 at Stanford University.

Development of Better Conceptual Models for Fractured Reservoir Rocks

Conceptual models for fractured systems were touched upon at the workshop, and the subject was again mentioned by two respondents. Rephrased as a question, a problem statement would go as follows. "Is it possible to characterize the fracture systems of geothermal reservoirs, and if so do the characteristics fall into specific types that would be useful in locating drilling targets and aiding in reservoir modeling"? For the purposes of history matching production data and estimating pressure declines, the reservoir engineer's conceptual model for the fracture system need not be geologically and hydraulically accurate. Such accuracy is not required by the physics because of the volume averaging effects and the diffusive nature of the processes. On the other hand, the geologist is required to develop as quickly as possible a physically realistic model of the fracture system based on woefully incomplete data. Even where good data are available, the best conceptual models are likely to be inadequate. There are several reasons for such a statement:

(1) Although many fracture zones are known to persist to depth, fracture orientations that one discerns at the surface will not necessarily be the same at reservoir depths.

(2) Stochastic and discrete models of a fractured region usually do not account for the rare feature with both large extent and large effective aperture that dominates the hydrology, the so-called "superconductor".

(3) Most real fractures do not behave as the idealized opening of fixed aperture between two parallel plates. Normal stresses and fracture fillings, among other factors, cause a tortuosity in the flow channel such that the flow system behaves more as a system of interconnected and braided pipes (Tsang, 1984). This model of fractures would appear to explain several paradoxes that have been reported: (a) why most of the fluid entering a borehole often comes from one (or at most a few) fractures, and not necessarily from the zone of highest fracture density; and (b) why the equivalent apertures derived from tracer migration and constant head permeability measurements on a single fracture differ by many orders of magnitude (Abelin et al., 1983). A combination of tortuosity and finite fracture lengths also explains why fluid entries of closely spaced wells often appear uncorrelated when plotted in cross-section, and show little communication when tested.

If we are to have better conceptual models they will have to evolve from many careful studies of fracture systems, active and fossil, thermal and non-thermal, and the development of physical models of bulk fractured rocks. The fracture systems would have to be related to the thermal-tectonic history of the region and to the water-rock geochemistry as well.

JOINT EFFORTS BY INDUSTRY AND DOE

Representatives of geothermal companies at the workshop expressed the thought that there could be more joint research efforts between their companies and DOE contractors. The fact that there have been few joint efforts is viewed as a matter of DOE and its contractors not taking the initiative. The following topics were suggested as possible ones for joint research:

- Sharing of efforts and results for integrated borehole, surface, and surface-to-borehole surveys.
- Closer collaboration on the application of geophysical methods (surface and drillhole), geochemistry and tracer studies.
- Collaboration on a major, multidisciplinary case history study of fractured systems.
- Joint research associated with existing DOE-Industry programs such as the Cascade Drilling Program.
- More active dialogue between DOE-sponsored groups and Industry to discuss and assess technological problems.

FUTURE WORKSHOPS AND SYMPOSIA

There was unanimity on the question of future workshops and symposia. All felt that one day was too little time to cover all that needed to be discussed, and that there should be another session at least two days in duration. Some of the special topics suggested for a future workshop are the following:

- nature of fracture permeability,
- geologic and geochemical studies for well placement,
- post-drilling borehole studies, and
- field case studies that include integrated approaches.

It was also expressed that an expanded workshop also include relevant material being gathered in other geotechnical studies, such as those related to the underground storage of nuclear waste. We are presently looking into the feasibility of holding an extended workshop or symposium.

SUMMARY AND CONCLUSIONS

An informal workshop on Fracture Detection and Mapping was held under the auspices of the LBL Advisory Panel on Geothermal Reservoir Technology and the Geothermal Technology Division of DOE. The main purpose of the workshop was to effect better technology transfer from DOE researchers to the geothermal industry. A questionnaire dealing with current and possible future DOE research and with potential areas for jointly sponsored DOE and industry projects was distributed to the participants. Although only about 25 percent of the participants responded with written comments, it was clear to us that the responses indicated three areas of concern: locating fractures and zones of high permeability prior to drilling; identifying major permeable zones during drilling; and developing better physical and conceptual models of fractured geothermal reservoirs. The respondents agreed that an extended workshop or symposium is needed, and we are now looking into this suggestion.

ACKNOWLEDGMENTS

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TABLE 1

ATTENDEE LIST
FRACTURE WORKSHOP
11 July 1985
Lawrence Berkeley Laboratory

Name	Affiliation
Craig Beasley	UURI
Sally Benson	LBL
Bill Berge	Grace Geothermal
John Henry Beyer	Consultant
Jim Combs	Geothermal Resources Intl., Inc.
Lea Cox	LBL
William Dailey	LLNL
Mel Erskine	Consultant
David D. Faulder	Chevron Geothermal Co. of Calif.
Norman Goldstein	LBL
Leigh House	LANL
Gerry Huttrer	Geothermal Systems
Joe Iovenitti	Thermal Power Co.
Paul Kasameyer	LLNL
Lewis Katz	Utah Geophysical
Art Lange	Albireo Ltd.
Ki Ha Lee	LBL
Marcelo Lippmann	LBL
David Long	Grad. Student with Al Waibel
Ernie Majer	LBL
Glenn Melosh	Unocal-Geothermal
Larry Meyer	LBL
Marty Molloy	DOE/SAN
Malcolm Mossman	Santa Fe Geothermal
Robin Newmark	LLNL
Dennis Nielson	UURI
Richard Parizek	Penn State
Dean Pilkington	Steam Reserve
Marshall Reed	DOE/GTD
Susan Spencer	INEL
Al Waibel	Columbia Geoscience

TABLE 2

Agenda
Informal Workshop on
Fracture Detection and Mapping

11 July 1985
Bldg 50A, Fifth Floor Conference Rm
Lawrence Berkeley Laboratory

8:30 AM	
Opening Remarks	Norman Goldstein LBL
	Joe Iovenitti Thermal Power Co.
Fault and Fracture Studies Based on Aerial Photographs	Dick Parizek Penn State
Fault and Fracture Mapping Based on Enhanced LANDSAT Imagery	Mel Erskine Consultant
GEOLOGICAL STUDIES	
Permeability in the Cascade Range	Al Waibel Columbia Geoscience
Predictive Structural Models for the Development of Fracture Permeability in Geothermal Areas	Dennis Nielson UURI
11:00 AM	
SURFACE GEOPHYSICAL STUDIES	
Overview of Surface Geophysics	Norman Goldstein LBL
Seismic Emissions and Microearthquakes	Lewis Katz Utah Geophysical
1:15 PM	
BOREHOLE STUDIES	
Hydrofracture Experiments at Beowawe and Fenton Hill	Leigh House LANL
The Tidal Strain Technique	Paul Kasameyer LLNL
Pressure Transient Detection of Fracture	Sally Benson LBL
Application of Electrical Geophysics to the Detection and Delineation of Fracture Zones	Craig Beasley UURI
Low-Frequency EM Fracture Detection	Ki Ha Lee LBL
Vertical Seismic Profiling	Ernie Majer, Larry Myer LBL
4:30-5:30 PM	
General Discussions	

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