GEOTHERMAL INJECTION MONITORING PROJECT
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ABSTRACT

The objective of the LLNL Geothermal Injection Monitoring Project is to evaluate the feasibility of using remote geophysical techniques to monitor the movement of injected brine. The ultimate goal is to develop a monitoring system including witness wells and geophysical measurements that indicates where injected brine is moving. Accurate determination of the response of the reservoir to injection would have both environmental and reservoir development applications. An effective monitoring system would guard against potential groundwater contamination and aid the efficient development of the reservoir.

In phase I of the project, the following activities have been completed:

0 State and Federal regulations have been reviewed to establish what monitoring will be required.
0 Selected case studies have been reviewed to illustrate the capabilities of present technologies.
0 Regimes around an injection well have been analyzed in order to select monitoring approaches that might be useful.
0 A general evaluation of the potential of these methods has been completed.
0 Promising approaches which could add a new dimension to existing capabilities have been identified for further evaluation.

In future work, an evaluation of the application of promising methods at specific sites and design of field experiments will be completed. These field tests will rigorously evaluate the potential usefulness of promising monitoring approaches.
I

INTRODUCTION

L. Younker
The Injection Technology Meeting held December 1, 1981 in Oakland sponsored by the D.O.E. established that development of approaches and tools to determine the path of injected fluid migration through a geothermal reservoir should be a high priority item in an overall injection research program. Accurate determination of the response of the reservoir to injection would clearly have both environmental and reservoir development applications.

In order to achieve this goal, participants at the meeting identified four major areas of suggested concentration within the general area of fluid migration research. These are 1) "developing various useful tracers to track fluids accurately, 2) developing geophysical and other techniques for tracking fluid migration accurately, 3) developing generic modeling techniques to predict fluid migration, and 4) effectively assessing fluid migration impact to optimize placement of injection wells".

These are of course not independent or competing research efforts but instead represent the four interacting areas of expertise which will be required to design an overall successful injection program. Point 4 is the major objective; where should injection wells be placed, and what injection strategy should be pursued in order to most efficiently develop the reservoir and meet environmental regulations? Because extensive spatial direct sampling of the fluid as it migrates through the reservoir is impossible, ultimately the success of an injection program will require the use of numerical modeling techniques to predict the fluid migration over the projected time frame of the field development. The long term success of a given injection program is therefore dependent on the site specific reliability of the numerical model. Monitoring approaches such as those identified in points (1) and (2) should be
used to select, refine, and validate the numerical model used at any particular site. An ideal monitoring methodology would use observations in existing wells and surface observations as the first step in testing the applicability of a given reservoir model. These observations would also indicate locations where additional monitoring wells would supply the most information about the reservoir behavior. Higher resolution, more expensive monitoring approaches which allow the fluid movement to be accurately tracked might then be considered at selected key areas within the reservoir if the situation warranted it.

The overall objective of the Livermore Injection Monitoring Program to date has been to assess the types of information potentially available from surface and borehole observations about the migration of injected fluids from a well. The critical question we have considered is what observations can be made which could be useful in site specific selection, refinement and validation of geothermal reservoir models applied to injection. Our program in FY81 was concerned with identifying approaches which could be useful, and making a preliminary evaluation of their potential application. Our present program is concerned with design and completion of limited carefully controlled field tests to rigorously evaluate the potential usefulness of the most promising approaches.

Table I-1 gives an overview of our Geothermal Injection Monitoring Program. The general plan for the project has involved preliminary studies leading to two decision points before full scale field work begins. In Phase I, we have completed a general evaluation of the types of monitoring needed and the potential of different methods for monitoring brine movement.
The basic question considered regarding monitoring needs was whether additional monitoring approaches are either necessary or desirable. To answer this question, we completed the following activities:

1) State and Federal regulations have been reviewed to establish what monitoring will be required.
2) Selected case studies have been reviewed to illustrate the capabilities of present technologies.
3) Geothermal reservoir development plans have been reviewed to identify additional areas where monitoring techniques would be useful.

Our technical evaluation of possible monitoring approaches was aimed at answering three questions:

1) What types of anomalies will be expected to appear in the region around the injection well?
2) What techniques should to be sensitive to those anomalies?
3) What instrumentation will be required to carry out the monitoring?

Our preliminary analysis of regimes around an injection well indicated that several approaches were worthwhile to consider. In order to assess the possible application of these approaches, we have used computer code calculations, reviewed and analyzed literature case studies, and drawn analogies with ongoing related field experiments. Based on our analysis of monitoring needs and scientific feasibility, we have identified promising approaches to be evaluated more fully at specific sites.
The general plan for this project involves preliminary studies leading to two decision points before full scale field work begins.

**Phase I: FY81/82**
- A general evaluation of the types of monitoring needed and the potential of different methods for monitoring brine movement.
  - What approaches look promising?
  - What are the questions to be resolved?
  - What types of experiments should be considered?

**Phase II: FY82**
- Evaluation of the application of promising methods at a specific site, and design of field experiment.
  - Should a field test be conducted?
  - Where should the test be conducted?
  - What are the potential scientific gains?

**Phase III:**
- Field experiment to test overall monitoring methodology.

Table I-1.
Summary

The feasibility of using remote geophysical techniques to monitor the movement of injected brine has been evaluated. We have established to our satisfaction that no single approach is likely to be identified that can be used to accurately monitor the precise location of the injected fluid. Several approaches have been considered in parallel because they add new dimensions to the existing monitoring capabilities, and are likely to cover a range of applications at a variety of geothermal sites. These include:

1. Microseismicity - a seismic net is used to record small magnitude events associated with injection;
2. Streaming potential - self potential anomalies produced by a moving fluid identify fluid flow direction;
3. Cross borehole geotomography - two-dimensional image of flow pathways is constructed using electromagnetic waves;
4. Well pressure response to solid earth tide - changes in pore pressures are used to discriminate fracture/pore porosity and estimate fracture orientations.

After remaining questions of resolution and the role of site specific conditions have been addressed, the four approaches in combination with conventional techniques will provide more detail about the geothermal reservoir. This information can then be used to refine the reservoir model and optimize the location of new monitoring wells.
GEOTHERMAL INJECTION: ANALYSIS OF MONITORING NEEDS

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Introduction

In order to insure that the technical results of the project have direct applications, we were asked to review and analyze the potential monitoring needs associated with geothermal injection. Critical questions considered in this task included:

- What regulations are now in place that apply to injection?
- What technologies are available to comply with regulations?
- Can these existing approaches satisfy the regulations in a reliable and economic way?
- Are additional approaches needed and/or useful?
- If feasible, how would a remote monitoring approach be incorporated into the overall monitoring system?
- Are there other areas of application where remote monitoring approaches would be useful?

In this section, we review the results of the analysis. We first summarize substantive environmental regulations relating to water quality. We then analyze other possible areas including environmental and reservoir management in which enhanced monitoring capabilities would be desirable. We next briefly and subjectively review the present monitoring capabilities, with an eye toward identifying areas where the present capabilities could be improved. Finally, we use the results of these three analyses to focus the current project to research areas which would have direct and immediate applications.
Water Quality Regulations

Introduction. All injection wells are now controlled by the EPA through the Underground Injection Control program (UIC). This is in addition to existing state control programs in virtually all states having geothermal production.

EPA Regulations. The UIC program establishes the criteria for state programs and the lead agency for the state program has a Director who is empowered to issue permits for injection wells. No permit may be issued if the Director has reason to believe that contamination of a drinking water aquifer will result. While there are many additional requirements for various types of injection wells, the Director has discretionary authority to go beyond them if he believes that contamination may result from a given operation.

The primary purpose of the UIC is to protect drinking water aquifers. Precise definition of a drinking water aquifer is difficult because a conservative requirement has been written into the law, stating that waters with salinity as high as 10,000 mg/l TDS must be protected. Most hydrologists would agree that water containing greater than one-third of this salinity would be considered for reclamation only in very unusual circumstances. There has been intense controversy leading to negotiations and out-of-court settlements, and the present regulations define an Underground Source of Drinking Water (USDW) as an aquifer containing water with salinity less than 10,000 mg/l TDS; exemptions from resulting regulations may be granted in a number of cases where it can be shown that it is unlikely that the water ever will be used for drinking water. In a recent out-of-court settlement, it was
stipulated that all aquifers containing water with more than 3000 mg/l TDS will be exempted. Thus, a _de facto_ definition of an USDW is:

An aquifer containing water with salinity less than 3000 mg/l TDS that is used or could reasonably be used for drinking water for human consumption.

The presence of an USDW in the area of influence of an injection well triggers many requirements under the regulations. If it can be shown that there is no USDW present, the Director is empowered to waive unnecessary regulations and in practice, most of the requirements would be waived.

UIC regulations divide injection wells into five classes; at present, geothermal wells are classified Class III, whereas geothermal reinjection wells are Class V. Class III regulations are quite comprehensive, while Class V wells have virtually no mandated requirements. The Director retains discretionary powers to control any injection well handling noxious fluids if an USDW is present.

State regulations. There are also state regulations on geothermal injection wells; all the Western states where geothermal projects are likely have such regulations. In practice, they are largely based on California regulations developed by the state Division of Oil and Gas (DOG), with added requirements or deletions based on local requirements. Information detailing some of these regulations exists in a set of reports prepared by the Geothermal Environmental Overview Project carried out by LLNL between 1978-80. These cover requirements for such states as Oregon, Nevada, Utah, and New Mexico—as well as for the geopressed resource in Louisiana and Texas.
Regulations in the state of California delegate the responsibility for preventing contamination of useful drinking or irrigation water supplies to the DOG. The DOG requires high standards of performance and the requirements are specifically designed for each injection system. The program apparently has been successful in that we know of no case where contamination of a useful source of water has occurred.

Summary. In Table II-1, we provide a simplified summary of the existing requirements and present uncertainties with respect to the water quality requirements. An important consideration is the question of which geothermal resource areas are located in regions that also have an underground source of drinking water. A preliminary analysis of this question indicates that many geothermal areas are not located in regions with extensive underground aquifers that need to be protected by water quality regulations.
Table II-1. Summary of requirements and uncertainties in water quality regulations.
Additional Monitoring Requirements

In Table II-2 taken from Younker et al. (1981), we identify a range of beneficial and undesirable factors that must be considered in the design of an injection program. Complying with environmental regulations and protecting water supplies is only one of several major objectives of a well designed program. In order to achieve these objectives, the fluid must flow predictably once injected into the subsurface formation.

A fluid monitoring system which responds to the movement of the fluid and thereby tests the predictions of reservoir modeling can be an integral part of the success of an injection program. For example, if water supply, heat extraction from the rock matrix, or reservoir pressure maintenance are objectives of the injection program, then fluid flow directions and rates around the well must be consistent with reservoir model calculations. Unpredictable flow could seriously jeopardize the long-term economic feasibility of the power plant. A monitoring system could be used to signal unpredictable flow and lead to the implementation of corrective measures prior to the development of serious environmental or production problems. Conversely, if the flow is consistent with the reservoir model calculations, then extrapolations based on the reservoir model are warranted and could guide the future resource exploitation program in a manner that is efficient and consistent with environmental regulations.

A monitoring system around a brine injection well is therefore essential not only to comply with water quality regulations, but is also essential to insure that all of the objectives of the injection program are realized. It is probably in the area of reservoir development and exploitation that enhanced monitoring techniques will find the most immediate application.
Table II-2. Desirable and Undesirable Factors Influencing the Design of an Injection Program

<table>
<thead>
<tr>
<th>Desirable</th>
<th>Undesirable</th>
</tr>
</thead>
<tbody>
<tr>
<td>o Mitigate subsidence</td>
<td>o Interference with heat output of producing well</td>
</tr>
<tr>
<td>o Disposal of waste fluids away from surface water and shallow aquifers</td>
<td>o Induced seismicity</td>
</tr>
<tr>
<td>o Maintain reservoir pressures</td>
<td>o Contamination of ground water resources</td>
</tr>
<tr>
<td>o Method to extract heat in rock</td>
<td>o Excessive power requirements to pump fluid</td>
</tr>
<tr>
<td>o Supply of water to producing reservoir</td>
<td>o Reduction of permeability and plugging of wells due to hydrothermal alteration</td>
</tr>
</tbody>
</table>
Monitoring Capabilities

In a simplified sense, we can list several questions that ideally should be answered by an efficient monitoring scheme. These include:

1) Did the fluid enter the intended injection zone?

By intended injection zone, we simply mean the subsurface formation bounded vertically by reduced permeability into which the operator expects the injected fluid to flow.

2) What is the spatial pattern of the fluid migration into this region? Are these preferred flow pathways or is the fluid advancing uniformly into the region?

3) Are there excursions of fluid out of the injection zone into other formations; most notably shallower formations?

4) Are there excursions of original formation fluid into other aquifers as a result of the injection?

5) Are the local drinking water aquifers being contaminated by the injection process?

Clearly if there was a monitoring scheme which could efficiently answer these questions then the major objectives of an injection program could be more easily achieved. In Table II-3, we provide a simple assessment of the present capabilities contrasted with monitoring requirements and objectives.
<table>
<thead>
<tr>
<th>Monitoring Objective</th>
<th>Comments</th>
</tr>
</thead>
</table>
| 1. Insure integrity of well                            | 0 Required in regulations  
0 Existing technology adequate                             |
| 2. Map advance of fluid into injection zone            | 0 Not required in most areas unless  
A) Subsidence problem  
B) Unusually low TDS  
0 Necessary for reservoir management  
0 May be necessary to achieve 3 & 4  
0 No existing technology to achieve in economic way |
| 3. Detect excursion out of injection zone              | 0 May or may not be necessary for regulations  
0 Necessary for reservoir management and subsidence control |
| 4. Detect migration into underground source of drinking water | 0 Subject of most regulations  
0 Existing technology adequate to detect  
0 Difficult to prevent unless 2 and 3 are achieved |

Table II-3. Summary of Major Monitoring Objectives and Capabilities.
In column one, we list major monitoring objectives consistent with the list of questions above, and in column two, we make some comments on the present situation. Our prime objective in this project is to identify economical geophysical approaches which could help to achieve monitoring objectives two and three and thereby contribute to the efficient exploitation of geothermal resources.
III

GEOTHERMAL INJECTION MONITORING

OVERVIEW

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J. Hearst
Introduction

In order to evaluate whether remote geophysical techniques can effectively monitor the movement of injected fluid, one must first consider the physical nature of the injection process. This will determine how physical and chemical properties change as a result of injection, what geophysical techniques could be sensitive to the fluid movement, and how the remote measurements must be positioned in order to maximize the possibility of detection. In a previous document (UCID-19066), we have identified the major regimes which radially surround an injection well. In this section, we provide additional background information on the relationship between these regimes and the feasibility of remote monitoring.

Transport vs. Pressure Monitoring Techniques

There are two fundamental approaches to the problem of estimating the path of injected fluids. The first approach is the direct method of sensing differences which the injected fluid has from the formation into which it is being injected. These methods fall within the category of "transport techniques", and include tracer methods, resistivity, IP, SP, and geotomographic methods. The second approach is the suite of various pressure monitoring techniques which may allow for the indirect estimation of the path of injected fluid. These methods include conventional well testing, solid earth tidal strain methods, pore pressure induced microseismicity, and pore pressure induced elastic strain and tilt measurements. These methods may have the ability either to estimate the spatial distribution of permeability around an injection well or measure the indirect effects of increased pressure. In the latter case, which includes pore pressure induced microseismicity, strain,
or tilt, one is left with the additional complication of unfolding the coupled elastic-fluid flow problem. An example of this complication is that of the Wairaki geothermal system in New Zealand, where the maximum surface subsidence bowl is located several kilometers from the production wells.

It would seem that, from the definitions given above, the best approach to monitoring the path of injected fluid would be the suite of direct methods. These have been used to a considerable degree in the past (with the exception of geotomography) for estimating the location of fluid conduits in groundwater, geothermal, and petroleum reservoirs. These methods do, however, have their respective drawbacks which require consideration in development of an optimal monitoring scenario. These include such questions as whether or not an anomalous signal can be detected (which depends on target size and depth as well as the contrast in physical parameters between the injected fluid and the host rock) and the signal propagation speed. The question of signal detection is addressed elsewhere in this report. The following is concerned with signal propagation speed, why it is important, and how it differs between the transport approach and pressure monitoring approach in the fluid injection problem.

Signal propagation speed is the rate at which an anomalous perturbation, associated with fluid injection, propagates into the formation. Thus, the signal propagation speed will determine the volume of reservoir "seen" by some sensing technique given a finite-duration monitoring test. This is of fundamental importance for injection scenarios for 20 or 30 year reinjection
lifetimes. For example, typical Basin and Range geothermal systems consist of roughly horizontal, moderately confined, aquifers intersected by near-vertical high-permeability fracture zones separating horst and graben features found commonly in areas undergoing regional tensional tectonism. Let us say that, hypothetically, little is known about the location of these fracture zones. If a direct approach reinjection monitoring experiment takes place over say a 10-year period, it may be concluded that the reinjected fluid is migrating radially outward from the injection well, a path characteristic of a uniform horizontal aquifer. If, however, monitoring is halted after 10 years based on the conclusions of this experiment, contamination of a shallow aquifer via a nearby high-permeability fracture zone might well take place some time after the conclusion of the 10-year direct monitoring experiment. The lesson to be learned from this example is that the suite of direct monitoring techniques provide no predictive capability in determining where the fluid will go. They serve, primarily, to determine where the injected fluid has gone. Therefore, direct monitoring methods must be carried out for the expected lifetime of reinjection. Pressure monitoring methods, on the other hand, provide a predictive capability, due to the propagation speed of pressure signals in permeable formations. In order to quantify the relative propagation speeds of direct and indirect monitoring methods, we consider the following simple example.

Consider a confined homogeneous aquifer intersected by an injection well. Assuming a constant mass injection rate Q which begins at t=0, one can
easily show that the pressure isobars propagate away from the well at a velocity

\[ v_p = \frac{2k \rho}{\mu S_s} \cdot \frac{1}{r} \]

where \( k \) and \( S_s \) are the permeability and specific storage of the aquifer, respectively; \( \mu \) and \( \rho \) are the viscosity and density of the fluid, respectively; \( r \) is the distance from the injection well and \( g \) is the acceleration due to gravity. For most aquifers, specific storage can be approximated by the expression:

\[ S_s = \rho g \left[(1-\varphi) C_r + \varphi C_f \right] \]

where \( \varphi \) is the formation porosity and \( C_r, C_f \) are the rock grain and fluid compressibilities, respectively. Thus, we can write

\[ v_p = \frac{2k}{\mu(1-\varphi)C_r + \varphi C_f} \cdot \frac{1}{r} \quad (1) \]

On the other hand, an element of fluid injected into the formation, under the same condition of constant mass injection, travels with a velocity

\[ v_t = \frac{Q}{2\pi \varphi \rho} \cdot \frac{1}{r} \quad (2) \]

where \( h \) is the thickness of the aquifer and \( Q \) is the mass injection rate. The ratio of pressure pulse velocity to transport velocity is therefore given by:

\[ \frac{v_p}{v_t} = \frac{4\pi \varphi \rho T}{\mu Q[(1-\varphi)C_r + \varphi C_f]} \quad (3) \]
where $T = \text{hk} = \text{transmissivity}$. Taking typical values of $S$, $\mu$, and $\rho$ of $10^{-10}$ Pa$^{-1}$, 0.3 cp, and 10$^3$ kg/m$^3$, respectively, we find that

$$\frac{V_p}{V_t} = 4.2 \times 10^{17} \frac{\varphi T}{Q}$$

where $T$ is in m$^3$ and $Q$ is in kg/sec. If we further assume other realistic values of $\varphi=20\%$, $T=0.5 \times 10^{-10}$ m$^3$ and $Q=50$ kg/sec, we will find that

$$\frac{V_p}{V_t} = 8 \times 10^4$$

Thus, we see from this simple example that the pressure signal propagates several orders of magnitude faster than the transport signal.

It is of some interest to note from equations (1) and (2) that: (a) the pressure signal velocity is independent of flow rate and formation thickness; and, (b) the transport signal velocity depends on both flow rate and formation thickness but is independent of permeability. The latter, however, may influence flow rate from the standpoint of injection pressure required to meet a given flow rate.

The implications of the above simple example indicate that, if pressure signal information can be correctly interpreted, then some prediction of where injected fluid may migrate can be made. The direct monitoring approaches can then be of considerable use in confirming these predictions and in improving the resolution of the indirect approach.

III-5
Anticipated Effects Associated with Transport Phenomena

As noted above a critical factor which determines the feasibility of the transport methods is the question of detectability. A prime consideration is whether the parameter contrast associated with the injection process is large enough for detection. In order to assess this factor, we have developed a simple computer code which calculates changes in resistivity, p-wave velocity and bulk density of a porous sandstone as functions of porosity, water saturation, sodium chloride concentration in the saturating water, temperature, and differential pressure. The methods used in the calculation assume a sandstone with intergranular porosity that obeys Archie's and Wyllies laws (Hearst, 1981). This code can be used in conjunction with reservoir simulators (Hanson, 1978) which calculate the temperature, pressure, and fluid characteristics as a function of time around an injection well to estimate target characteristics as a function of time.

As an illustrative example, consider two alternative injection scenarios. In the first case, fluid with a temperature of 50°C and salinity of 10,000 ppm is injected into an aquifer of 200°C and the same salinity. This would be an expected situation if waste fluid with little surface processing is injected into the producing horizon. The monitoring strategy under this scenario would be to detect the thermal front and from that infer the position of the fluid front. Our estimates for this case indicate seismic velocity changes on the order of 10%, resistivity changes by a factor of 3, and negligible changes in density associated with the thermal differences. As an alternative scenario, consider the case in which the injected fluid and aquifer have the same temperature; however, significant differences in fluid
chemistry exist between the injected fluid and the in situ formation fluid. This might be the case if high salinity waste fluid is injected into a shallow horizon. The monitoring strategy in this case would be to attempt to directly infer the fluid boundary. For a range of scenarios, we anticipate resistivity changes of 2 to 3 orders of magnitude, and significant density differences. In the individual analyses that follow these types of estimates are used to evaluate the general feasibility of a given geophysical technique.

Evaluation of Alternative Monitoring Approaches

We have selected a range of geophysical approaches which might be useful for injection monitoring. This include both methods which respond to the transport effects, and methods which respond to pressure effects. Methods originally selected include microseismicity, streaming potential, borehole gravity, well pressure tests, resistivity and induced polarization, cross borehole EM Transmission, cross borehole seismic, and a variety of methods which respond to induced elastic strain.

These monitoring approaches were evaluated in Phase I of the project using computer code calculations, experience gained in previously completed directly related field experiments, experience gained in ongoing field experiments which are analogous to the injection monitoring problem, and thorough review and analysis of case studies from the literature. In this report, we concentrate on the following methods:
In each case, we have relied heavily on the tools and experience which have been developed in other programs at LLNL over the past several years.

Summary

Regimes around the injection well provide targets for remote detection. The targets could be regions with different temperature, pressure, fluid composition, mineralogy, or state of stress. The positions of the boundaries of these regions and the contrast in properties across the boundaries depend on the details of each particular site and the injection strategy. The boundaries may be sharp or gradational. Some of the boundaries may advance with the injected fluid; others may not move or may lag or lead the injected fluid. In order to evaluate the usefulness of a geophysical method, we must understand how the anomaly it detects relates to the movement of injected fluid at a particular type of geothermal field. Ultimately, achieving this understanding will require the design and completion of carefully controlled field tests. As a first step in this report, we complete a preliminary feasibility study of several promising approaches.
IV

GEOTOMOGRAPHY FOR MONITORING FLUID FLOW IN GEOTHERMAL FLUID REINJECTION

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William D. Daily
Introduction

Geophysical tomography or "geotomography" is a remote sensing technique which has been applied to several problems requiring underground imaging (e.g., Lytle et al., 1976; Davis et al., 1979; Okada et al., 1980).* This technique has been used to study subsurface fluid flow and is a promising candidate for monitoring the location of brine as it is injected in a geothermal area. Tomography, a concept originally developed for medical imaging, is a means by which a cross-section of a region can be remotely imaged. Here it has been adapted for use underground to give a cross-sectional image of the plane defined by two boreholes. Radio frequency electromagnetic (EM) waves are transmitted between two boreholes along many different ray paths (as shown in Fig. IV-7), and signal attenuation is measured along each path. Different attenuation will be measured along each ray path because each path will have a different length, and will traverse a portion of subsurface where the electrical conductivity and permittivity are different. From orientation of the ray paths, their lengths, and the measured signal attenuation along each ray, an image of attenuation factor, α, can be generated. Since geothermal fluids tend to have high salinities, the formation saturated by injected brine may have attenuation factors of sufficient contrast from the surrounding rock that the fluid front can be located. For this reason, we expect to be able to detect an image of the attenuation factor obtained from geotomography.

* Lytle et al. (1981) have studied in some depth the application of geotomography to monitoring subsurface fluid flow.
Evaluation of geotomography as a monitoring tool for underground fluid flow, requires consideration of several questions:

- how easily can the technique be deployed given engineering constraints imposed by a typical geothermal brine reinjection operation.

- how large a region can practically be monitored using geotomography?

- what electromagnetic contrasts are required between the formation saturated with reinjected brine and the rock mass ahead of the saturation front for adequate detection?

In this paper we address these questions using computer simulations of tomographs expected from brine reinjection and calculations of system parameters central to any monitoring effort using tomography.

Theory

A typical data collection scheme used for geotomography is illustrated in Figure IV-1. Radio frequency signals are transmitted from an antenna in one borehole through the region to be imaged to a receiving antenna in another borehole. Many source receiver locations are used along the boreholes to generate a large number of transmission paths through the region of interest. The electromagnetic properties between the boreholes affect the signal amplitude and phase along each path. The absolute attenuation along each ray is measured and the received power \( P_{\text{rec}} \) is related to the transmitted power \( P_{\text{tr}} \) by

\[
P_{\text{rec}} = \frac{P_{\text{tr}}}{4\pi^2} f(\theta) G_{\text{tr}} A_{\text{rec}} e^{-2\alpha r},
\]

Where

- \( \theta \) = orientation angle between transmitter-receiver antennas
- \( r \) = distance between antennas
\[ G_{tr} = \text{gain of transmitter antenna} \]
\[ A_{rec} = \text{effective area of receiving antenna} \]
\[ f(\theta) = \text{effective combined radiation pattern of antennas} \]
\[ (\text{we use } f(\theta) = \sin^4 \theta) \]
\[ \alpha = \text{effective attenuation factor along the ray path (inverse electromagnetic skin depth).} \]

We assume in this equation that the subsurface is nearly homogeneous, that reflections from the surface or other interfaces are weak, and that the receiver is in the far-field radiation pattern of the transmitter. Subsurface homogeneity is a good assumption in many cases. Surface reflections can be minimized using techniques employed by Lytle et al. (1976). The quantities \( P_{rec} \) and \( P_{tr} \) are measured while \( r \) and \( \Theta \) are calculated from the known arrangement of boreholes and antenna positions; \( G_{tr} \) is the transmitter gain for an electromagnetically short dipole; and \( A_{rec} \) is the receiver effective area which is measured in the laboratory.

To construct a tomograph of the region between two boreholes (as in Fig. IV-1), we divide the region into many cells each with electromagnetic attenuation parameter \( \alpha \). The measured attenuation along each ray path is then equal to the sum of the differential attenuations within each cell along the ray:

\[ \sum_{i=1}^{N} \alpha_{ij} d_{ij}, \]

where \( \alpha_{ij} \) and \( d_{ij} \) are the attenuation factor and ray path length, respectively, in the \( i \)th cell for the \( j \)th ray, and \( N \) is the number of cells along the ray path \( j \).

IV-3
The collection of these summations for each ray path between the boreholes gives a set of \( j \) equations that can be solved for the attenuation factor in each cell. Details of the data analysis and tomograph image reconstruction algorithm used for the data reported in this paper are given by Dines and Lytle (1979).

Tomographs of subsurface electrical permittivity \( \varepsilon \) can be made from measurements of signal phase change with an incremental frequency change along each ray path. When conduction currents are small compared to displacement currents:

\[
\frac{\varepsilon}{\varepsilon_0} = \left( \frac{c}{r} \frac{\Delta \phi}{\Delta \omega} \right)^2,
\]

where \( \varepsilon_0 \) is free-space permittivity, \( c \) is the speed of light and \( r \) is the path length. The phase change \( \Delta \phi \) is measured over a small swept-frequency interval \( \Delta \omega \). For this tomograph the measured phase change along each ray is the sum of the phase shifts within each cell:

\[
\frac{1}{c} \sum_{i=1}^{Nj} \left( \frac{\varepsilon_{ij}}{\varepsilon_0} \right)^{1/2} d_{ij}.
\]

which is analogous to the previous case.

Calculation of the attenuation factor and permittivity for each cell also allows construction of a tomograph of electrical conductivity \( \sigma \), because

\[
\alpha = 2\pi \frac{\lambda_0}{\lambda} \left[ \frac{1}{2} \frac{\varepsilon}{\varepsilon_0} \left( \sqrt{1 + \tan^2 \delta} - 1 \right) \right]^{1/2}
\]

where \( \lambda_0 \) is the free-space wavelength, and \( \tan \delta = \frac{\sigma}{\omega \varepsilon} \) (Von Hippel, 1954).
Capabilities of Geotomography from previous Field Experience

Constraints imposed by a variety of conditions in the field are very important in the design and execution of any field experiment. Inadequate management of constraints like costs, time limitations, available facilities, instrumentation temperature range, etc., can turn an otherwise practical experiment into an impossibly difficult one. The purpose of this section is to review pertinent experimental procedures and system parameters of cross-borehole probing, in light of previous field experience. We speculate about problems unique to a geothermal injection experiment, and finally evaluate geotomography as a practical technique for characterization of geothermal brine injection.

For geotomographic mapping, it is generally desirable to locate the borehole pairs at the maximum practical spacing. Increasing the borehole spacing usually means fewer holes and less cost to image a given volume. Optimal hole separation is difficult to predict because it depends on many parameters such as signal loss in cables, environmental electrical noise, and the electromagnetic properties of the ground.

The primary consideration for optimal borehole separation is the effective electrical attenuation factor $\alpha$ characteristic of the region. Figure IV-2 shows the calculated signal strength which would be measured as a function of signal path length for various average attenuation factors. Typical noise levels restrict field experiments to signals greater than about -100 dBm. Attenuation constants depend on the characteristics of the rock (especially its water content) and signal frequency. Generally $\alpha$ is proportional to $(\text{frequency})^{1/2}$ indicating that lower frequencies are
desirable for long transmission paths. However, spatial resolution in the
tomograph increases as the frequency increases so that a compromise must be
made between desired resolution and hole spacing. For typical frequencies of
1 to 50 MHz attenuation constants usually range from 0.1 to 1.0 nepers/metre; an exceptionally low-loss rock such as a dry granite (e.g., Lytle and Lager, 1976) may have a approximately equal to 0.04 at 30 MHz. Experience
indicates that high resolution tomography in such a low-loss material is
easily possible over distances up to about 70 m. However, in more typical
rock types, as may be expected in a geothermal field, a practical borehole
separation is from 8 to 50 meters. Prediction of a more definite borehole
spacing for a geothermal brine injection experiment requires laboratory
measurements of attenuation constants and permittivities at frequencies
between 1 and 50 MHz for core samples from the formation into which the brine
is to be injected. This is important for meaningful experiment planning. We
expect that frequencies less than 30 MHz will be required in geothermal
application except where exceptionally fine detail is required.

Of interest in a geothermal brine reinjection experiment is the time
development of a fluid front as it moves from the injection point. Assuming
gematography can image this front, it is desirable that data collection times
be small compared to the time scales of interest in the brine flow so that
"snapshots" of the front could record its movement. Our field system has
recently been automated to allow more rapid acquisition of the large quantities
of data required for each tomograph. The system now automatically moves the
antennas, records the data on magnetic tape, and plots the data for real-time
examination. Actual tomographs are processed on one of the laboratory
computers. (We are developing a system which constructs tomographs in the
field.) For typical tomographs with horizontal extent of 20 meters and antenna spacing of 0.5 m (1600 data points), data collection requires 2-4 hours. This time increases approximately as the square of the number of antenna positions along each hole. Of course the image resolution depends on, among other things, the density of rays in the image plane so that a compromise is necessary to obtain an image with acceptable resolution in a reasonable time. We expect that data for each tomograph could be collected in a few hours. This should be acceptable because subsurface flow rates are often slow enough to yield time scales of days for flow over a few tens of meters. Where permeability is dominated by cracks or fractures with much larger flow rates, tomography could be used to image the region before injection and then again after flow is established. The change in the two images would delineate the flow paths. The Applied Technology Group at LLNL has already successfully mapped fluid flow through fracture zones by tomographic methods (Deadrick et al., 1981; Ramirez et al., 1982).

It is important to note that previous geotomographic experiments employed simple measurement of amplitude of electromagnetic waves. Greater distances could be achieved, even at high frequencies, if additional measurement techniques were employed. These methods include stacking of data, correlation techniques, and time averaging. Such methods are easily added to the present technique.

Equipment used for geophysical tomography has been designed specifically for a wide range of field applications. The downhole antennas are compatible with three inch or larger inside diameter boreholes, either uncased, or cased with an electric insulator, such as plastic or fiberglass. Electromagnetic
signals will not propagate through metal casing, although sections of a borehole from which tomography is not to be performed can be cased with metal. Measurements can be made from either dry or water-filled holes; however, at water depths greater than about 300 m sealing antennas and cables against leaks becomes difficult. Also, at this depth, signal attenuation due to the long cables can require the use of special low-loss cable. The temperature limit for most downhole instrumentation is about 150°C; however, the most sensitive receiving antennas which contain downhole electronics are limited to operation below approximately 80°C. Measurements from holes above 80°C would require the use of a passive receiving antenna which could be constructed for temperatures of about 150°C.
Computer Studies of Possible Geothermal Situations

Synthetic tomographs were generated using a computer to evaluate the effects of several important parameters on the image of a subsurface brine flow. These parameters are:

1. Size and orientation of the region saturated with the reinjected brine.
2. Electrical contrast of the brine saturated rock with respect to the undisturbed formation.
3. Ambient electromagnetic noise.

We have used specific models of electromagnetic attenuation to represent a wide variety of brine flow possibilities. In each case, we are assuming that the formation permeability is dominated primarily by flow along fractures. Fluid movement away from the fracture walls, through the competent part of the rock mass, results in a halo of brine saturated rock along the length of each fracture. This saturated halo contrasts electromagnetically with the surrounding rock and therefore can be imaged.

The character of the halo will depend on the fluid permeability of the intact rock, pressure gradients forcing fluid into the rock and the time fluid has been diffusing away from the fracture. Model electrical parameters are the electrical conductivity and permittivity of halo and surrounding rock. Models used in the calculations are shown in Figure IV-3. These models were initially analyzed as tomographs without noise in the data. These calculations show that for the chosen range of model parameters, some fractures are more easily resolved than others.
The larger anomalies, about 5 meters thick, were easily resolved at both conductivity contrasts \((\sigma_{\text{halo}}/\sigma_{\text{formation}})\) of 10 and 100. The thinnest anomaly (1 cm) was used to model flow through a fracture with no diffusion of brine into the unfractured rock. It is evident that a single brine-filled fracture of this nature cannot be imaged using geotomography. As shown by Model 5, orientation of the flow direction in the tomographic plan can also be determined. However, some distortion of orientation and shape of the flow front is present, especially when the fracture is not symmetrical with respect to the tomograph ray pattern.

The effects of data noise are also shown for each model in Figure IV-4. A Gaussian distribution of noise with a mean equal to 10 percent of the signal amplitude and variance was added to the data for each model calculation. This noise tends to reduce the contrast between the anomaly and the background and degrade the edge definition in the image. As might be expected, low contrast features suffer these problems more than higher contrast fractures, although with a ten percent noise level, the anomalies shown in Figure IV-4 are still well defined. The low contrast \((\sigma_{\text{halo}}/\sigma_{\text{formation}} = 10)\) case for Model 5 was studied with noise up to 60 percent of signal strength. In all cases, the anomaly was imaged although somewhat distorted and ill-defined in horizontal extent.
A Tomographic Experiment Illustrating Subsurface Flow Monitoring

To illustrate the capabilities of cross-borehole electromagnetic tomography to map subsurface fluid paths, we describe the results of a field experiment performed at a test site near the town of Oracle, Arizona, 45 miles north of Tucson (Deadrick et al., 1981, Ramirez et al., 1982). Three coplanar boreholes separated by 9 and 6 m, each 91.4 m deep in fractured granite were used at the site. A concentrated brine was circulated between the outer two holes for several days to replace the natural ground water with a solution of greater electrical contrast relative to the surrounding rock mass. Then tomographs were made from 26 and 91 m depth between the holes, 9 m apart. The tomographs show several regions of high electromagnetic attenuation, some intersecting only one of the boreholes, some traversing the region between the holes. These high attenuation zones were inferred to be brine saturated regions of high fracture density in the rock mass. This interpretation was supported by analysis of single borehole wireline logs from the holes bounding the tomographically imaged region. Caliper, acoustic velocity, and neutron logs were used to determine where fractured regions intersected the boreholes. Perturbations in the wireline data indicative of fractured rock correlate well with the high attenuation regions of the tomograph which intersect the boreholes. Of course, only the tomograph can provide information on the brine content of the rock mass between the boreholes. Therefore, the wireline logs do not provide direct evidence of the capabilities of geotomography to image brine-filled fractures, but they do provide indirect corroborative data which supports our interpretation of the tomographs. Results of this experiment show that cross-borehole tomography is useful in mapping subsurface flow in fracture zones.
Recommendations

Tomography is suitable for imaging fluid flow in rock provided the fluid offers sufficient electrical conductivity contrast to the medium. In cross-sections of 10-30 meters, computer studies indicate that small fracture zones are detectable but single cracks are not detectable. The "Oracle" experiment indicates that a practical frequency range is 20 to 50 MHZ for measuring fluid flow; however, the best frequency range depends on the rock's electric properties and the distance between boreholes.

For long distance studies of fluid flow, several alternatives are possible. Previous experiments show that one can transmit radio frequency waves in the ground over a few km if one uses frequencies in the KHZ range. More distance is probably achievable for higher frequency electromagnetic waves if "stacking", correlation methods, or time-averaging techniques are employed. Up to now, there has been no need for better measurements of the wave amplitude than what is already provided by the present equipment. Long distance tomography needs further development, but would be a worthwhile technique to further investigate and develop.
Figure IV-1. Schematic of a two-borehole tomographic survey. One receiver is lowered into one hole and one transmitter is lowered into another hole. By varying the depth of location and relative positions, the transmitter-receiver system can measure signal along many different ray paths.
Figure IV-2. Calculated signal strength as a function of signal path length and attenuation constant.
Figure IV-3. Basic geometries to represent various fluid flow situations.

Background values
\[ \sigma = 10^{-2} \text{ S/M} \]
\[ \epsilon = 9 \]

Anomaly
\[ \sigma = 10^{-1} \text{ to } 1 \text{ S/M} \]
\[ \epsilon = 9 \]

Exception: Case 4
\[ \epsilon = 81 \]
Figure IV-4. This is a sequence of tomographs with increasing amounts of noise. The object is an idealized sloping fracture zone (see Fig. IV-3, example 5) with background conductivity $10^{-2}$ S/M, anomaly conductivity $10^{-1}$ S/M, and relative electrical permittivity of 9.

Noise acts to distort the shape of the anomaly: a) no noise; b) 10% gaussian noise; c) 20% noise; d) 40% noise; and e) 60% noise.
V

APPLICATION OF MICROSEISMICITY TO
GEOTHERMAL INJECTION MONITORING

A. Smith
Introduction

One of the primary objectives of a geothermal monitoring program is to deduce the subsurface flow of the injected brine. The actual migration of the brine depends on the permeability of the medium and injection pressure. The pressure front resulting from the injection will give an indirect measurement of the brine front within the aquifer. If we can map this pressure distribution, it will provide a predictive tool to indicate the future path of the brine front.

Microseismicity may provide a technique to map this pressure distribution. Earthquakes are a well documented phenomena associated with the injection of fluids (Evans, 1966; Ohtake, 1974; Raleigh, 1979; Fletcher and Sykes, 1977; Hsieh and Bredehoeft, 1981). Information provided on both the Denver seismicity and the Rangely experiment demonstrate the sensitivity of earthquake sequences to the details of the fluid pressure distribution (Dieterich et al., 1972; Hsieh and Bredehoeft, 1981). In each case the occurrence of microseismicity depends on exceeding a threshold pressure within the reservoir. In addition, the pressure distribution controls the spatial occurrence of the earthquakes. Thus, the distribution of earthquakes allows us to map the migrating pressure pulse. Knowing the pressure distribution in the reservoir allows us to predict the future movement of the injected fluid.

Many geothermal reservoirs and associated aquifers are fracture dominated, and similar in this respect to the Denver and Rangely cases. In these examples, the microearthquakes were found to be caused by a release of tectonic stress triggered by increasing pore fluid pressure. Consequently,
their occurrence depends on the magnitude of tectonic stress, the original fluid pressure distribution, the injected pressure distribution, heterogeneities in the geology and hydraulic characteristics of the reservoir. For the occurrence of microseismicity in Denver the pressure increase was 32 bars over hydrostatic; at Rangely it was approximately 70 bars. In the case of Denver, it was concluded that the instantaneous shut-in pressure of 17 bars above hydrostatic was just sufficient to cause fractures to remain open, and is equal to the regional stress component oriented normal to the fracture plane (Hsieh and Bredehoeft, 1981). At greater pressures the transmissivity abruptly increases as rapid flow occurs in the fractures (Raleigh, 1972). In an operating geothermal reservoir, this may also occur during reinjection of the brines.

Application of the above concepts on microearthquake and injection pressures to the mapping of the pressure distribution from reinjection in geothermal reservoirs depends on both the local reservoir conditions and the detection and mapping of any microseismicity. Although The Geysers is a special case, spatial distribution in the seismicity in the geothermal field suggests that it is induced by production; however, its physical origin remains unclear (Bufe et al., 1981; Allis, 1981; Eberhart-Phillips and Oppenheimer, 1981).

In fracture and fluid dominated reservoirs such as Raft River, no unusual seismicity has been observed during injection experiments (S. Spencer, EG&G, personal communication, 1981). For Raft River, this may result from the short duration of the tests, from insufficient fluid pressure or tectonic stress, or from unfavorable reservoir characteristics. On the other hand, the seismic
stations employed were not optimum for the detection of microseismicity because only three seismic stations were used, and the magnitude detection threshold is relatively large for a conclusive experiment.

Negative results for injection-induced seismicity have also been reported for areas with injection under gravity flow at Viterbo, Italy, and Otaki, Japan (Cameli and Carabelli, 1976; Kubota and Aosaki, 1976). At East Mesa, California, injection tests did not produce earthquakes greater than magnitude 1.75 (Crittenden, 1981).

Brine injection is now occurring in the Cerro Prieto field in Mexico without any associated increase in seismicity near the well (E. Majer, personal communication, 1982). The limited recharge is occurring in the older portions of the field; however, one might not expect increased seismicity since previous withdrawal would have reduced the original fluid pressure.

Hydraulic fracturing at the Hot Dry Rock Geothermal Site near LANL generated abundant microseismicity (Pearson, 1981). The granitic rock has relative low matrix permeability and required 200 bars injection pressure to promote fracturing. The small magnitude and high frequency content of the induced seismic events required an adjacent borehole seismometer for detection. Active crosshole experiments indicated the orientations of the fractures based on clever interpretation of the seismograms (Aki et al., 1982). These experiments are not directly transferable to the usual geothermal reservoir, but the results are intriguing and provide useful analogues.
The design of an experiment to detect potential microseismicity in a geothermal region using surface seismometers is a critical problem. In the following sections we will evaluate an analogue deployment at the Nevada Test Site (NTS) to detect microseismicity following an explosion. This will serve as an example illustrating some of the capabilities and analysis techniques developed within the Seismic Group at LLNL. Next, a comparison of ASP (Automated Seismic Processor) and the LLNL processing approach will be used to demonstrate the need for complete digital recording of each event for later processing. Final design considerations for a seismic experiment will be reviewed together with the trade-offs. These lead to recommendations for a possible deployment.

NTS Post-shot Experiment

Approximately two months following the COLWICK nuclear test on Pahute Mesa, an array of nine Sprengnether DR-100 digital recorders with S-4500, 4.5 Hz, three-component seismometers were deployed in a small array. The array is illustrated in Figure V-1. Telemetry was used for the more distant stations. A DR-101 Array Trigger provided common triggers to all the DR-100s through hardwire connections. The result is a common time base for all the instruments; the array trigger provides simultaneous start times to each digital recorder and eliminates any problems of clock drift between elements of the array. Sampling was at 100 Hz for this experiment. The array also reduces triggers to local noise: a specified number of seismometers must detect an event before the array is triggered.

During approximately two weeks of recording time, 45 events (between -1.5 and 0. local magnitude) were detected and located. Portable field equipment
was available for confirming the operational reliability of the DR recorders and the written tapes. This expedites correction of any problems. Reading and processing of the digital cassettes is accomplished on the Seismic Group's Prime 750 computers. Tapes are read into files for rapid review and automatic picking using our Seismic Analysis Code (SAC). This program package allows rapid display of all the stations in user specified format. For example, Figure V-2 displays only the vertical components for an event starting with those near the center of the array. This system allows rapid discrimination of events within the array from regional events or sonic booms. Figure V-3 is a record section for the COLWICK event. Each seismogram is plotted as a function of distance from the epicenter; again this is essentially automatic once the event is located. Array processing (f-k plots, etc.), filtering, power spectral analysis, and other techniques are also available in an interactive mode within SAC.

Location procedures include the more traditional HYP071, and a highly stable location program which searches for the minimum least-squares solution within a specified volume. An example for the previous event is given in Figures V-4 and V-5. The two-sigma volume is given, rather than an estimate based on the partials as in HYP071. The solutions are particularly stable for events outside of the array since the routine can avoid local minimums and, instead, searches for the absolute minimum of the residual. The velocity model is still critical: In this case interval velocity logs and Vibroseis logs are available. This problem will be discussed in a later section. Finally, computer programs are routinely used for moment inversion and joint velocity/hypocenter inversions.
In conclusion, this deployment demonstrates state-of-the-art acquisition of microseismic data and automated processing. These facilities are in a constant state of improvement and include more than a dozen DR-100, a similar number of PDR-2 (with GOES and special array triggers), telemetry, and portable readers. In addition, a new LSI/11 based acquisition system has been designed in conjunction with Woodward-Clyde and will soon be in operation on our Livermore Network. The system operates with approximately 64 channels and performs event detection and automatic picks. The results together with the actual data are archived on 9 track tape from the internal disk, and the large storage capacity allows for infrequent servicing. A field-hardened version is planned when full operational reliability is proven on the Livermore Local Seismic Network. A second LSI/11 based system is planned for immediate location and analysis of events; however, the actual data will still be retained for later analysis using SAC.

ASP Calibration Experiment

To evaluate ASP (Automated Seismic Processor), an experiment was conducted with Ernest Majer of the Lawrence Berkeley Laboratory. Fifteen stations from the Livermore Local Seismic Network were used as the input to ASP for automatic location and analysis. The results have been recently outlined in McEvilly and Majer (1982).

The network at LLNL is also an automated system based on an HP-1000 computer which detects possible events using an array trigger and stores them for future analysis using SAC. During a five week period when ASP was operating, the LLNL system detected 20 local events that were located with
high quality. ASP also detected all these events; however, only 12 were located, and of these, only 3 produced good locations. The experiment illustrates the limitation of a half-space model for event location. This can be partially corrected by use of a gradient over half-space model. The results also suggest that full post-processing reduced the number of false alarms and increases detection probability.

ASP determines a number of important seismic parameters such as seismic moment for each event, but it does not save the actual trace. This is a major flaw for a study of microseismicity in a geothermal region. First, the original data is unavailable to improve picks or study the characteristics of the waveform. Better velocity models and possible inversion methods often make this desirable. Relocations and inversions will be very important for defining the migration of fluid and the pressure front. Until seismicity is proven to be a useful tool for monitoring injection, careful analysis using sophisticated methods on the digital traces represents the optimum approach.

Design of Seismic Experiment

Monitoring and locating microseismicity in an active geothermal production zone presents special challenges. High seismic noise, depths up to 5 km, and small event magnitudes will make detection and location of events especially difficult. These conditions will dictate the essential features for any seismic experiment.

Any network will require array triggering of three-component seismometers in order to suppress false triggers on the digital recorders. The total number and design of the seismometers depends on their placement: shallow or
surface placement will detect relatively low-frequency events due to attenuation along the path. Attenuation and higher seismic noise will also limit the magnitude threshold compared to a borehole instrument. A deep borehole instrument will also constrain the location solutions. Unfortunately, borehole instruments are limited by both temperature and expense. These represent significant tradeoffs between borehole and near-surface placement of the seismometers.

The placement of borehole instruments in relatively shallow monitoring wells would be a possible alternative. Their depth would reduce seismic noise (if there is no activity), but hopefully not exceed the temperature specifications of the geophones. Ten hertz geophones would give a sufficiently broad frequency response and, if three-component, allow polarization filtering and component rotation for detection of shear phases. The majority of seismometers would be located near the surface and would again be broad-band, three-component digital systems.

An optimum system would include high-capacity, 9 track tape for archiving any events; a short term, controlled experiment could be conducted using digital tape cassettes for storage as found on PDR-2 or DR-100 recorders. A minimum of 200 hz sampling would be needed for recording microseismicity.

If microseismicity is to map the pressure front, the relative and absolute location of seismic events must be accurately known. This, of course, requires a good knowledge of the velocity structure. Some information would be available from velocity logs, but joint inversion of velocity and location would be essential (Taylor and Scheimer, 1981). Controlled shots at
known depths and at various surface locations would provide the proper calibration. These can be done any time during the deployment if events are detected. Alternately, these active experiments can be expanded to examine evidence of anomalous velocity distributions and the existence of open fractures (e.g. Aki et al., 1982). Again a trade-off of resources exists and a possibility for collaboration with other interested groups.

Finally, if events are indeed mapping a pressure front, independent techniques will be necessary to confirm these results. These might be obtained from an alternate, remote geophysical technique, actual downhole pressure measurements, and chemical sampling for the brine front. Control of the injection will be necessary to correlate events with depth, flow rate, duration, and cycles of injection. These are, of course, site specific parameters. Appropriate reservoir models would probably be necessary to relate the various measurements, and to establish a series of predictions that can be used to further support and improve the entire analytic system.

Recommendations

Microseismicity offers the hope of directly mapping the pressure front associated with brine reinjection. There are several site specific problems to be solved for successful application: (1) the magnitude of local tectonic stress and fluid pressure; and (2) reservoir characteristics. Given well-head pressure tests and well-logs for a given site, the likelihood of success can be estimated (Hsieh and Bredehoeft, 1981).

The detection of measurable microseismicity is also site dependent. The amount of background seismic noise, occurrence of high attenuation paths
between sources and receivers, and the complexity of velocity structures at the site introduce special problems. The following features are apparent for any site:

1. Near-surface geophones will probably not be sufficient; a few borehole instruments would provide additional information and constraints on the seismicity.

2. Digital recording with a minimum of 200 Hz on three-components would provide the necessary frequency content for surface geophones. Borehole seismometers may require a higher sampling rate. Automatic gain-ranging as found on PDR-2 would provide a wide-dynamic range and help to avoid missing small events that are hard to detect because of background seismicity. The trace information must be saved: automatic processors such as ASP which do not save the original traces are not appropriate for a highly experimental situation such as this. ASP, however, may prove to be useful as a backup for testing production configurations.

3. Velocity models are crucial to obtain the best possible locations of the seismicity. Both velocity logs and refraction surveys would be needed. In addition, depth resolution can be improved by using surface and downhole shots which allow three-dimensional velocity and hypocenter inversions and station corrections (e.g. Taylor and Scheimer, 1981).

An initial experiment would be primarily limited by resources. A simple, low-cost experiment would involve only a surface array using digital recorders with an array trigger. This would be similar to the NTS COLWICK post-shot
experiment and would span a sufficient dimension to resolve depth variations. The results, however, would not be conclusive. Borehole instruments might provide additional sensitivity and resolution, which may prove essential for this problem. However, the additional expense is significant. Finally, another improvement would be the field-hardened, digital-telemetry recording system being developed at LLNL. This would provide high-capacity storage and long unattended periods without servicing, plus the ability to use sophisticated analytical tools in the Seismic Analysis Codes available on the LLNL systems.
Fig. V-1.
A. Location of array stations (S335, etc.). The origin is ground zero for the shot, and the axes denote 200 meters in the positive X and Y directions. The box indicates the 2 sigma epicentral location for the event in the following figures.
Fig. V-1

B. Epicentral locations for detected aftershocks where the symbol indicates the type and depth range. The aftershocks cluster around the Colwick shot location and along a NW to SE trend.
Fig. V-2. Plots of the vertical components recorded for the aftershock.
Fig. V-3. Record section plotted using SAC for distance from the epicenter.
Fig. V-4. Plot of epicentral location for event. Information as in Fig. V-1A.
CURRENT ROTATION  X = 89.00  Y = 10.00  Z = 2.00

X ROTATION -

Fig. V-5. Plot of hypocenter in 3D space. Stations are along the surface (X-Y plane) and focus is indicated by asterisk. The box encompasses all solutions within two sigma of the residual. All other information is similar to Fig. V-1A.
VI
UNCONVENTIONAL PRESSURE MONITORING TECHNIQUES

J. Hanson
Introduction

Well testing involves perturbing the reservoir fluid pressure from its equilibrium state in order to evaluate hydraulic and elastic parameters of the reservoir rock. In conventional well testing, the perturbation source can be considered a point or line source corresponding to the well completed in the formation. On the other hand, solid earth tidal strain and barometric pressure fluctuations by their very nature perturb the entire reservoir. As a consequence of the differences between these two approaches regarding the type of reservoir loading involved, one might expect that one method may yield information about the reservoir that the other may not. Indeed, we have found over the past two years that the two methods can complement each other (Hanson, 1979 a&b, 1980, 1982; Hanson & Bodvarsson, 1978). This short note briefly outlines a part of our recent work on evaluating the structural nature of the Raft River geothermal reservoir based on an analysis of well pressure response to tidal strain and barometric pressure loading. It should be kept in mind that the data available were taken during conventional well testing experiments and were not tailored for our particular experiment. Nevertheless, these "second-hand" data have yielded some interesting results regarding structural control of the reservoir and the nature of the production zones at each well. Preliminary analysis was completed in FY80 as part of the advanced reservoir assessment project for the LLNL Geothermal Program. Work this past year has refined the method and led to procedures for estimating the spatial orientation of the preferred flow conduits.

Approach

Measured wellhead pressure is the sum of pumping, tidal, and barometric effects. When nearby well pumping is occurring, the barometric effect is
typically masked and is difficult to retrieve from the signal. We have developed a numerical procedure that is capable of separating this component and placing a measure of confidence on the separation. Figure VI-1 shows an example of the application of this procedure for the extraction of the barometric response at two wells, RRGE-3 and RRGI-7, in the Raft River geothermal reservoir. The correlation coefficient between measured barometric pressure and the associated wellhead pressure response extracted from the raw wellhead pressure data was found to be greater than 0.8 for four of the six wells observed and greater than or equal to 0.95 for two of the six wells. (A correlation coefficient of 1.0 implies a perfect "one-to-one" correspondence between two signals.) From this analysis, the barometric efficiency (BE), namely the ratio of wellhead response to barometric pressure load, can be computed.

Figure VI-2 shows the computed barometric efficiency for the six wells analyzed at Raft River. The large variation observed in barometric efficiency within a single reservoir suggests a link between BE and heterogeneity of rock properties. This variation is closely connected to the nature of porosity (pore or fracture) in the production zone and will be discussed later. Having found the barometric response and pumping response for a well, both of which are derived by a numerical procedure referred to earlier, one can then subtract these effects from the raw wellhead pressure data to leave only the response of the reservoir to solid earth tidal strain. The latter response is then analyzed using spectral analysis methods to obtain the reservoir fluid pressure amplitude response (admittance) and phase response at the various tidal frequencies.
Our analysis has been confined primarily to five frequencies corresponding to the two diurnal tides ($O_1$, lunar; $K_1$, solar) and the three semidiurnal tides ($N_2$, lunar; $M_2$, lunar; and $S_2$, solar). Figure VI-3 shows an example of the results of this procedure applied to data taken at RRRGI-7 in the Raft River reservoir. Details of our spectral analysis method have been presented elsewhere (Hanson, 1979) and will not be discussed in this note. From this information and an appropriate well-reservoir model, one can calculate the reservoir specific storage coefficient ($S_s$) or, equivalently, the porosity-total compressibility product ($\phi C_t$).

By itself, neither the barometric efficiency (obtained from the barometric pressure response) nor specific storage (from tidal strain response) is particularly enlightening with regard to the nature of the production zone. However, using a first-order model of barometric response, one can apply a very simple analysis to show that the formation porosity $\phi$ is proportional to the product of barometric efficiency and specific storage, where the proportionality constant depends only on known reservoir fluid parameters. Although this model is no doubt over-simplified, we have found that this kind of approach clearly allows for identifying the nature of the production zone porosity. This is to be contrasted with conventional well-pumping methods that, by themselves, can only yield the products $\phi C_t$ or $\phi C_t H$, where $H$ is the formation thickness. Having estimated $\phi$, one can then separate out $C_t$ from the $\phi C_t$ product.
Interpretation - Raft River Example

Table VI-1 shows a summary of the results of this analysis applied to the Raft River wells. The values of $C_t$ based on tidal analysis are consistent with those evaluated using conventional well testing. The Table shows that a very low value of porosity was obtained for RRGE-1, 2, and 3. These wells are at least partially completed in fractured crystalline rock composed of metamorphosed quartz and shist, quartzite, and quartz monzonite. Wells RRGE-1 and RRGE-2 intersect the N-S trending Bridge fault, and RRGE-3 penetrates the NE-SW trending Narrows Structure. This information is based on regional geophysics and geology and water chemistry studies. The small observed porosity and large total compressibility are consistent with the hypothesis that the primary production for these wells originates in fracture-dominated production zones within the crystalline complex. On the other hand, wells RRGI-6 and RRGI-7, which are intermediate-depth injection wells, are completed in the sedimentary Salt Lake formation. The porosity estimates for these wells, 14% and 16%, are close to core analyses for the Salt Lake formation. The total compressibility at RRGI-6 is consistent with a "typical" compressibility for consolidated sandstone at the calculated porosity of 14%. The total compressibility at RRGI-7 is somewhat high but still of the proper magnitude for consolidated sandstone.

It is of interest to note that, even though the calculated barometric efficiency and porosity-total compressibility product both differ by more than a factor of two between RRGI-6 and RRGI-7, the calculated porosity differs by less than 2%. One mechanism that might account for this observation is
Table VI-1. Raft River Analysis - Estimates of formation porosity and compressibility for six wells.

<table>
<thead>
<tr>
<th>WELL</th>
<th>$\phi$</th>
<th>$C_T(\text{psi}^{-1})^{**}$</th>
<th>$S_s(\text{ft}^{-1})^{**}$</th>
<th>BE***</th>
<th>$\phi$</th>
<th>$C_T(\text{psi}^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRGE-1</td>
<td>13.3 x $10^{-7}$ ($O_1$)</td>
<td>1.4 x $10^{-7}$</td>
<td>0.08</td>
<td>0.01</td>
<td>31.8 x $10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>RRGE-2</td>
<td>5.1 x $10^{-7}$ ($M_2$)</td>
<td>2.2 x $10^{-7}$</td>
<td>0.18</td>
<td>0.04</td>
<td>14.2 x $10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>RRGE-3</td>
<td>5.3 x $10^{-7}$ ($M_2$)</td>
<td>2.3 x $10^{-7}$</td>
<td>0.24</td>
<td>0.05</td>
<td>10.6 x $10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>RRGE-4</td>
<td>8.2 x $10^{-7}$ ($M_2$)</td>
<td>3.5 x $10^{-7}$</td>
<td>0.75</td>
<td>0.24</td>
<td>3.4 x $10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>RRGI-6</td>
<td>5.3 x $10^{-7}$ ($O_1$)</td>
<td>2.3 x $10^{-7}$</td>
<td>0.69</td>
<td>0.14</td>
<td>3.8 x $10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>RRGI-7*</td>
<td>1.3 x $10^{-6}$ ($M_2$)</td>
<td>5.6 x $10^{-7}$</td>
<td>0.30</td>
<td>0.16</td>
<td>8.1 x $10^{-6}$</td>
<td></td>
</tr>
</tbody>
</table>

* average of data sets A & B

** from solid earth tidal strain analysis

*** from barometric pressure response analysis
aquifer leakage which would have the effect of reducing barometric efficiency and increasing the effective porosity-compressibility product. A more refined model than the one we have used in this analysis will be required to address this question.

Water chemistry suggests that RRGE-3 and RRGE-4 are completed in a zone whose waters originate in the Narrows Structure. Recalling that RRGE-3 penetrates fractured crystalline rock, and from the tidal and barometric analyses, has small indicated production zone porosity which is suggestive of fracturing, we were surprised that our analysis of RRGE-4 (which is of similar depth as RRGE-3) indicates that primary production in this well is pore and not fracture porosity. A closer look at the completion report for RRGE-4 of 1978, when it was deepened to 5100 feet, showed that although the deepened hole penetrated 450 feet into the quartz-monzonite crystalline basement, neither fractures nor improved production was seen. The obvious conclusion is that the primary production in RRGE-4 is from pore porosity and not fracture porosity, consistent with our tidal and barometric results.

Even though the kind of analysis presented above, using tidal strain and barometric response, is in a very early stage of development, the results have added another dimension to understanding the nature of structurally complex systems such as at Raft River. Considerable work needs to be done to build a firmer theoretical foundation for this approach and to test these methods in the field, but these early results are very encouraging.

Finally, we come to what may be the most useful application of the tidal strain methods. Because the diurnal and semidiurnal tides represent two
distinct modes of deformation, the associated crustal deformations will have
different, and non-isotropic distributions. For example, the maximum strain
in the horizontal plane for the lunar $O_1$ tide is in the E-W direction,
whereas the maximum strain in the same plane for the lunar $M_2$ tide is in the
N-S direction. These tides also have different deformation distributions for
non-horizontal directions. Figure VI-4 shows this distribution of tidal
deformation. If a discrete fluid-filled fracture with arbitrary orientation
and large permeability in an otherwise impermeable medium is intersected by a
well, the amplitude and phase of the pressure response of the fracture to
tidal strain will be determined by the fracture orientation. Reversing the
argument, the orientation of the fracture may be determined by measuring the
wellhead pressure response. Dr. D. Bower of the Gravity and Geodynamics
Division of Energy, Mines and Resources, Canada, has recently made use of this
phenomenon to characterize discrete fracture orientation in eight wells at
Chalk River (personal communication). Such an approach is ideally suited for
application to discrete fracture analysis.

In reservoirs with structurally controlled porosity, the use of tidal
strain response may allow for an improved characterization of the reservoir
when results are compared to those obtained by conventional well-testing
methods, which often lump structure into a simple model. An example of the
manifestation of structure in wellhead pressure data at the Raft River
reservoir is shown in Figure VI-5. Recall that RRGI-7 is completed in the
sedimentary Salt Lake formation. Conventional well testing places a
permeability-thickness product on this site on the order of 70,000 md-ft. A
mathematical model for tidal response under these conditions predicts no phase
shift between the pressure response at the well and the tidal strain and, indeed, at a 90% confidence level, none is observed in the data. The same is true of RRGI-6 which is completed in the same formation. However, a phase lead of roughly 30° is observed on the RRGE-3 semidiurnal tides. This well has a permeability-thickness product of the same order of magnitude as RRGI-6 and RRGI-7. The simple mathematical model for tidal response not only predicts no phase shift for this well, but also does not allow for a phase lead under any physically allowable circumstance. The mathematical model, which does not include structural effects, is obviously incorrect for this situation. The observed phase lead is therefore most likely a consequence of the fracture zone orientation in the crystalline basement penetrated by RRGE-3 on the Narrows Structure. To test this approach, we developed a computer code based on a simple fracture model. This model assumed that a flat fracture (or fracture zone) of very high permeability was embedded in an impermeable host rock (in the case of Raft River, this would correspond to the quartz monzonite basement). Figure VI-6 and VI-7 shows the results of this analysis. It is clear that the tidal strain approach is consistent with what is already known about fracture orientation at the Raft River geothermal system based on regional and borehole geology and geophysics.

For very high permeability fracture zones such as at Raft River, analysis of structurally controlled wellhead pressure response to tidal strain is a relatively straightforward problem. In "tight" structures, frictional effects may also influence observed wellhead pressure response, and this effect will add a further complication to the problem.
Summary and Application to Geothermal Injection Monitoring

Careful measurement and interpretation of pore pressure response to solid earth tides has the possibility of identifying the nature and orientation of the primary fluid conduits away from the injection well. This information would be useful for choosing a flow model for the injection zone and for identifying possible preferred flow directions. The appeal of this approach is that, unlike conventional well testing, pumping is not required, thereby, allowing for reliable and cost effective long term data acquisition. The target parameters for tidal reservoir testing are the same as conventional testing—namely, the fluid conductivity and reservoir storage. However, because of the tensorial nature of the driving force (tidal strain), the spatial orientation of the preferred flow conduits will be manifested in the well pressure record.

Future Work

Previous work done by LLNL on data taken at the Raft River Geothermal Area indicates that the nature of connected porosity (i.e., pore or fracture) and fracture orientation can be estimated from the analysis of pore pressure response to solid earth tidal strain. Development of appropriate theoretical models of these phenomena are in a very preliminary state. Therefore, we will propose to continue theoretical work parallel with implementing a field experiment. The theoretical part will include (1) resolution of fracture orientation method, (2) sensitivity of fracture orientation method to fracture permeability, (3) development of a more refined model for porosity evaluation in a fracture-dominated formation, and (4) continued improvement of data analysis methods including trend analysis and filtering.
The field experiment will involve instrumenting injection and monitor wells with either wellhead or downhole pressure gauges. Continuous monitoring of fluid pressure will be carried out with the instrumental wells shut-in or static for a duration not less than a month each. Atmospheric pressure will be measured simultaneously with the wellhead fluid pressure. It is hoped that nearby wells will not be undergoing pump tests during the tidal monitoring period as this complicates the data analysis which comes later. Results of the tidal analysis will be compared with known geological, geophysical, and hydrological data pertaining to the reservoir parameters in order to ascertain the feasibility of the tidal method. Site selection will be based on the accessibility of wells over periods of several months, the planned well-pump tests (if any), and the available information on production/injection formation type, structural control, and logs taken within the reservoir.
Fig. VI-1. Wellhead pressure data (top) and calculated wellhead pressure response to barometric pressure loading (bottom) for RRGE-3 and RRGI-7. The solid line (bottom) is barometric pressure recorded at the Pocatello airport. The pluses (bottom) are the computed barometric response of the well (raw data minus tides minus pumping effects) divided by the barometric efficiency.
Fig. VI-2. Computed barometric efficiencies for six of the Raft River wells. Error bars represent 90% confidence levels.
Fig. VI-3. Solid earth tidal strain response of wellhead pressure at RRGI-7 after correcting data for pumping and barometric effects. Admittance (a.) is a measure of the pressure change to the tidal gravity perturbation and the phase shift (b.) is relative to the tidal gravity perturbation. Error bars represent 90% confidence intervals.
DISTRIBUTION OF TIDAL DEFORMATION

Fig. VI-4. Spatial distribution of tidal deformation for the O₁ and M₂ tides.

Fig. VI-5. Phase shift of well head pressure response to tidal strain relative to tidal strain signal for RRGI-7(a) and RRGE-3(b). The lunar O₁ and M₂ tides have been found to be the best representative of diurnal and semidiurnal tidal response. The solar K₁ and S₂ tides are typically contaminated by air temperature effects at the wellhead. Error bars represent 90% confidence levels.
Fig. VI-6. Comparison of tidal strain estimates of strike with known regional structure at Raft River. Numbers in parentheses are pressure monitoring times for each well. 90% confidence intervals are indicated.
Fig. VI-7. Histogram of dip angles of fractures in cores taken from RRGE-1 and RRGE-5. Cores were taken within 200 m. of sediment-basement decollement. (Guth et al., fault and joint geometry at Raft River geothermal area, Idaho, July, 1981). Error bars (90% confidence) are tidal method estimates.
VII

APPLICATIONS OF SELF POTENTIAL IN MONITORING
FLUID FLOW IN GEOTHERMAL FLUID INJECTION

P. Kasameyer
introduction

The movement of fluid and/or heat through a porous medium can produce electrical potentials which are observable at some distance from the region where flow occurs. Thus, electrical potential measurements on the Earth's surface can detect both the effects of fluid flow, and of thermal gradients underground. The observed electrical potentials are called self-potentials (SP) to distinguish them from potentials which arise when the Earth responds to external currents generated either naturally or as a result of geophysical exploration. (SP also is used to indicate a source of potentials not considered in this summary, Spontaneous Potential.)

SP anomalies are used to explore for geothermal fields, and are often observed to correlate with regions of vigorous sub-surface fluid flow and high heat-flow areas. SP has also been observed on earthen structures in order to locate zones of rapid water seepage and to detect changes in the rate of seepage.

We are evaluating the possibility of using SP anomalies as part of a program to monitor the motion of fluid away from a geothermal injection well. Injection of fluid will produce an SP field whose spatial and temporal changes contain information about the evolution, direction, and magnitude of fluid flow, and the evolution of the temperature distribution around the injection well, as well as the nature of the rock formations surrounding the injector. If, for a particular injection well, the SP field can be shown to be large enough, inexpensive measurements could be made at many locations around the well. These measurements could yield inexpensive information about the geometry of fluid flow around the well (i.e., is it spherical or confined to a planar fracture?) which could be used for the effective placement of
injection, production, or monitoring wells and which would aid the development of accurate reservoir models. Furthermore, the SP field could be continuously monitored, alerting operators to unexpected changes in the fluid flow patterns. Thus SP could potentially provide an inexpensive way to continuously monitor geothermal injection.

The following contains a description of the status of the evaluation, which consists of a study of the literature on SP, both published and unpublished. First, the theory of the production of SP anomalies is discussed and it is shown that:

a) The magnitude and half-width of anomalies depend strongly on the geologic structures and rock properties, as well as the fluid flow and heat flow. Consequently, conclusions about the usefulness of SP will be very site dependent.

b) Some aspects of the theory are very new and have not been evaluated in the literature; furthermore, the authors disagree and there has been little verification of models with field data. Some additional theoretical work is needed to model injection-related anomalies. Second, examples of observed SP anomalies are discussed, and it is shown that the theoretical calculations of SP anomalies can be related to actual field examples. Finally, initial calculations indicate that it is plausible to detect the SP anomalies from geothermal injection, but that uncertainties in models and rock properties make it impossible to evaluate the usefulness of those anomalies at this time. A program to continue the evaluation is described.

Theory

The well-known relationship known as Ohm's Law describes the connection between electric currents and electric potentials in materials. It is less
generally known that other fluxes, such as heat flow, fluid flow, and chemical diffusion, can also produce electrical potentials. This cross-coupling can be observed in the laboratory (Ishido and Mizutani, 1981), and is the basis for SP logging (Teiford et al., 1976), and for the application of SP surveying to geothermal exploration (Corwin and Hoover, 1979).

The process and physical properties contributing to the formation of SP anomalies during brine injection are illustrated schematically in Figure 1. SP anomalies can be routinely calculated from assumed current and charge distributions in the ground. The relationship to the primary flow fields, in this case heat or fluid flow, is not completely understood, and has only recently been discussed in the open literature. Nourbehecht (1963) developed most of the theory and Fitterman (1978) reported Nourbehecht's work, and calculated analytical models of SP (and magnetic anomalies) associated with static pressure fields in dilatant zones prior to earthquakes. Sill (1981) developed a numerical method for the calculation of SP anomalies from static primary flows in complex geologic structures. Sill disputes the boundary conditions which Nourbehecht and Fitterman applied (constant fluid pressure at the earth's surface), so their results differ significantly, even for simple situations like a point source in a homogeneous half space. The theoretical approaches are described below in enough detail to illustrate the differences between different authors, and to indicate how their differences might be resolved.

The analysis of self potential fields is based on the observation that, in a permeable medium, various fluxes $F_i$ (such as heat flow, mass flow, current flow, etc.) result from gradients in several potentials $V_j$ (e.g., temperature, pressure, electrical potential, etc.). Therefore,
\[ F_i = G(\nabla W_1, \nabla W_2, \ldots) \text{ for each } i \]

where \( G \) is a general, unknown functional relationship. It is customarily assumed that the gradient terms are sufficiently small so that only linear terms need to be considered, as indicated by:

\[ F_i = -\sum L_{ij} \nabla W_j \]

As Nourbehecht (1963) points out, this assumption requires justification in each application.

The diagonal elements of the matrix \( L \) are well known: electrical conductivity, thermal conductivity, permeability/viscosity ratio, etc. The off-diagonal terms in \( L \) are cross-coupling coefficients which describe the secondary connection between flows and potentials. For example, the connection between pressure gradients and electrical currents is called the electro-kinetic coupling coefficient. The values of the primary conductivities and the cross-coupling coefficients can be measured on rock samples. These results are often reported as a ratio of \( L_{ij}/L_{ii} \), such as the streaming potential coefficient, with dimensions of voltage per pressure drop.

The methods used to calculate SP anomalies from specified pressure or temperature fields will not be reproduced here. The two published approaches will be described and their differences and limitations for the present application discussed.
Nourbehecht (1963) and Fitterman (1978, 1979, and 1979) share one approach (labeled here by N/F and illustrated in Figure VII-1). They combine all the primary potentials into a pseudopotential which obeys Laplace's equation in homogeneous zones, and calculate the contribution to that potential from apparent sources induced at zones where the properties change. This produces equations which can be solved analytically to calculate the pseudopotential everywhere on the surface. If the values of the other potentials are known on the surface, then the electrical potential distribution can be found from the pseudopotential. This method can be used to calculate SP anomalies for several fully coupled, static, flows, in several simple geometries (infinite half-space, horizontal layers, vertical fault, etc.), providing the boundary conditions can be stated in terms of the values of potentials such as pressure or temperature.

Sill's (S) approach is different because he assumes that the electrical potentials are so small that they produce negligible fluid and heat flux. Then, as shown in Figure VII-2, the fluid and heat flow can be found by conventional methods and put into a model representing the distribution of cross-coupling coefficients, which calculates the distribution of apparent sources. These sources are located wherever fluid or heat flow is perpendicular to a boundary. Finally he calculates the electrical potential from these sources, using a model for the conductivity distribution in the Earth. In each step the equations are solved numerically. Sill's method allows calculations for static flow fields in complex geometries, and allows the application of standard reservoir engineering and heat flow models with a variety of possible boundary conditions. The numerical calculation method of S is probably more costly to develop and more difficult to verify than the analytical method of N/F.
The two methods produce significantly different results when applied to similar problems. Specifically, 1). for a point pressure source in a homogeneous half space, N/F conclude that there is no SP anomaly, whereas S concludes there is, and 2). for a boundary where the coupling coefficient changes, N/F conclude that apparent sources are proportional to the value of temperature and pressure, and that the integrated SP anomaly is zero unless flow is parallel to the boundary, whereas S concludes the sources are proportional to the gradient of the temperature or pressure, and that anomalies are caused by flow through the boundary. These results have only been recently published and are being evaluated by the investigators and others at the present time. The first disagreement is caused by N/F and S using different boundary conditions for pressure on the surface. Unfortunately, both of their solutions are for unrealistic conditions and it is not possible to intuit what the results will be for conditions based on better reservoir models.

In order to use theoretical modeling to evaluate the feasibility of using SP to monitor geothermal injection, we need to be able to solve the coupled equations for the following conditions:

1. A reasonable, probably complex hydrogeologic structure, perhaps with several layers, vertical boundaries, or fault zones with high permeability.
2. Hydrologic boundary conditions which are appropriate, such as a confined, semi-confined, or water-table aquifer with injection at one or several points or lines.
3. Thermal conditions which are influenced by fluid flow as well as by conduction.

4. Time dependence of injection rate, flow field, or temperature.

The theoretical studies presently existing in the literature do not provide the means to solve this problem. N/F require pressure and temperature boundary conditions, not fixed flow rate or conditions appropriate for a confined or water table aquifer. Furthermore, their method requires the simultaneous solution of the thermal, mass, and electrical contribution to the pseudopotential. This may be too complicated in the case of coupled heat and mass flow. Sill's method can be more easily applied to complex hydrologic problems because the heat and mass flow are determined independently from the electrical potential. In fact, standard solutions from the geothermal reservoir engineering literature could be used as a starting point for his calculations. Unfortunately, his present calculations for pressure sources are for inappropriate boundary conditions and his numerical results cannot be extrapolated to more realistic models. Finally, the areas of disagreement between the different investigators must be resolved before their approaches can be applied with high confidence.

In summary, the presently published theoretical models cannot be directly applied to the calculation of SP anomalies around injectors. Several steps are required to make them satisfactory:
1. Choose a method to pursue. Sill's method looks the most promising because it can use results from standard and innovative reservoir engineering models to construct the thermal and flow fields, and can deal with complex geologic structures.

2. Re-evaluate the theory in order to a). determine the sources of disagreement between S and N/F, b). ensure that the assumed (and implicit) equations and boundary conditions for flow are consistent between the reservoir models and the electrical potential models, and c). evaluate the possibility that time dependent changes in the flow field will produce additional sources of electrical potentials.

3. Develop the capability to perform the calculations. This could involve modification of our transmission-line analogy calculation code, or by cooperation with Sill.

Interpretation of Field Data

Corwin and Hoover (1979) provide an up-to-date summary of SP surveys collected in areas of anomalous fluid and heat flow. They conclude that:

1. Measurements can be made to an accuracy of 5mV, while natural sources of noise can be much larger.

2. SP anomalies at geothermal fields can range in amplitude from 50 to 2000 mV, and are therefore easily detected.

3. Modeling techniques, and knowledge of cross-coupling coefficients are not yet adequate for detailed interpretation of these anomalies.

One example illustrates the uncertainties in interpretation. Corwin and others (1981) recently evaluated the SP anomalies observed at the East Mesa geothermal field. They were able to match the shape of the observed anomalies...
by postulating planar distributions of sources along known fault zones. Extensive drilling in the area provides enough data to understand the temperature and pressure fields. Corwin and his colleagues conclude that the sources are at least a factor of 10 larger than could be predicted from electrokinetic and thermoelectric coupling coefficients measured on samples in the laboratory. This kind of discrepancy between lab measurements and in-situ properties is typical of the few cases where SP anomalies have been related directly to flow fields. Recent laboratory studies, such as those by Ishido and Mizutani, (1981), indicate that temperature and ionic composition of fluids each have strong effects on the cross-coupling coefficients in sandstone, suggesting a mechanism for the discrepancy.

Because of the limitations of our knowledge of cross-coupling coefficients and the uncertainty in the applicability of the theoretical studies, it is felt that the field studies of SP anomalies produced by well-characterized sources of heat or fluid in an area with well-known geology, provide the best way to determine the amplitude and nature of SP anomalies. Underground nuclear tests are one such source. The data described below indicate that the theoretical analysis for thermal sources (where the boundary conditions are acceptable) predicts important features of the SP anomaly from two thermal sources.

In the early sixties, several investigators studied SP anomalies around underground nuclear explosions. Unfortunately, the results were generally unsatisfactory, and little of the work was published. Nourbehecht's (1963) thesis contains the most comprehensive attempt to explain the observations. He concluded that disturbance and re-equilibration of the water table near some explosions produced changing SP anomalies which persisted for several weeks. Additional measurements by J.H. Scott, R.D.Carroll and D.R. Cunningham
(personal communication) illustrate the effectiveness of the pseudo-potential method for explaining differences in SP anomalies produced from different explosions. Scott and his colleagues collected SP data in the vicinity of an underground explosion, BILBY. An extensive SP survey around BILBY was conducted several months after the detonation, and is shown in Figure VII-3. The survey also covered the location of an earlier explosion, AARDVARK. Both BILBY and AARDVARK produced transient SP anomalies which decayed over 30-50 days. These anomalies were attributed to pressure variations related to groundwater moved by the shots. In fact, BILBY was the first shot conducted below the water table, and that was the motivation for many of the studies which were performed. The data in Figure VII-3 were (apparently) taken more than 50 days after BILBY and more than two years after AARDVARK. The pressure transients have apparently decayed. A substantial SP anomaly remains at AARDVARK, but none is seen at BILBY. To the best of my knowledge, no one has explained this observation.

The data in Figure VII-3 can be explained by assuming that the persistent AARDVARK anomaly is a result of the temperature perturbation, which takes many tens of years to decay. If that is true, why is there no anomaly at BILBY? Figure VII-4 shows a cross-section from the BILBY area. The geology at AARDVARK is similar. Both shots took place in the tuff layer which is the most electrically conductive formation in the section (resistivity 60-80 ohm-m). The overlying alluvium and underlying Paleozoic rocks have higher resistivities, up to 1100 ohm-m. BILBY was fired deep in the tuff, as shown, and AARDVARK just below the alluvium.

Nourbehecht (1963) has calculated SP anomalies for the geometry shown in Figure VII-5-a, a hot sphere crossing a horizontal boundary. He calculates an attenuation factor for the thermoelectric potential, as a function of geometry.
and location. That factor is multiplied by an unknown coupling coefficient difference (C1-C2) and by the temperature of the hot sphere (assumed to be 70-80 degrees C in this case) to get the potential distribution. The shape and amplitude of that factor depend strongly on the resistivity contrast R21 across the boundary, as well as depth to the boundary (d), and the radius of the zone of overlap (a). For each shot, the parameters in the following table are estimated for the nearest boundary.

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Aardvark</th>
<th>Bilby</th>
</tr>
</thead>
<tbody>
<tr>
<td>d = depth of Boundary</td>
<td>1000 feet</td>
<td>3000 feet</td>
</tr>
<tr>
<td>R21 = resistivity contrast at Boundary</td>
<td>+0.90</td>
<td>-0.90</td>
</tr>
<tr>
<td>Maximum value of attenuation factor if a/d=0.5</td>
<td>more than 0.15</td>
<td>less than 0.06</td>
</tr>
<tr>
<td>Anomaly half-width</td>
<td>a/d=1.0, r = 1000 feet</td>
<td>a/d more than 5.0, r = 15,000 feet</td>
</tr>
</tbody>
</table>

From the table, we see that the AARDVARK thermo-electric anomaly should have a half-width of about 1000 feet, similar to that seen in Figure VII-3.
On the other hand, the thermoelectric anomaly for BILBY would be far more spread out, with a half-width of more than 15,000 feet, broader than the area of the self-potential survey. Furthermore, if the driving functions \((C_1-C_2)T\), are the same for both shots, then the amplitude of the anomaly caused by BILBY should be about one-third of that for AARDVARK, only 10-15 mV, an amplitude easily obscured by the natural variability. Clearly the thermo-electric anomaly caused by BILBY could not be detected by the data in Figure VII-3.

This analysis indicates that theoretical studies can provide insight into the causes of previously measured SP anomalies, and that the mechanisms of the production of these anomalies is at least partially understood. That, in turn, gives us confidence that, if SP anomalies due to injection can be observed at a location where the geology is understood, then inferences can be drawn about the depth of the flow region, and other attributes of the flow field.

Conclusions

The previous sections can be summarized as follows:

1. Recent theoretical studies indicate that it should be possible to predict SP anomalies resulting from injection.
2. Field observations with known sources and at geothermal fields indicate that the theory is generally correct.
3. Additional theoretical refinements are required before specific injection scenarios can be modeled with confidence.

4. There is considerable uncertainty about the possible range of coupling coefficients which might be found in the field.

Given the uncertainties listed above, it may be useful to determine if SP anomalies associated with injection can actually be detected in the field before proceeding on refinements of the theory and additional parameter measurements to improve our predictive ability. The brief calculation in the next paragraph indicates that it is plausible that SP anomalies due to injection could be measured.

Sill (1981) calculates SP anomalies for several different geologic structures. His results give a dimensionless voltage, $V_n$, which has a maximum value ranging from .01 to .15 for his models. The largest value is for a point pressure source in a homogeneous half-space, and the smallest is for a fault buried by a conductive overburden. For our purposes, these models are presumed to indicate the range of values which might come from a calculation of $V_n$ for a particular site. The real potential, $V$, is related to $V_n$ by

$$V = V_n (C I \frac{v}{k a})$$

where: $C$ = the cross-coupling coefficient for the medium (units of V/Pa)
$I$ = the injection rate (m$^3$/sec)
$v$ = the fluid viscosity (Pa s)
$k$ = the permeability (m$^2$)
$a$ = the depth of the injection point (m)
For a "typical" set of values listed below, the SP anomaly is large enough to be easily detectable.

\[
\begin{align*}
C &= 20 \text{ mV/atm} = 2 \times 10^{-7} \text{ V/Pa} \\
I &= 900 \text{ gallon/min} = 5.7 \times 10^{-2} \text{ m}^3/\text{sec} \\
v &= 0.01 \text{ poise} = 0.1 \text{ Pa s} \\
k &= 40 \text{ millidarcy} = 4 \times 10^{-14} \text{ m}^2 \\
a &= 500 \text{ m} \\
V_n &= 0.05 \\
V &= 28 \text{ mV}
\end{align*}
\]

This amplitude, 28 mV, is much larger than the 5 mV repeatability that Corwin has achieved. Thus, given the uncertainty in almost every parameter used in this calculation it is certainly plausible, but not demonstrated, that repeated measurements before and after injection, could detect an SP anomaly associated with reinjection.

A decision must be made whether or not to pursue SP as one means of monitoring the flow of injected fluid. The benefits are easily summarized: this is an inexpensive, continuous way of monitoring flow from the surface. In addition, any results of this study could be applied to other applications of SP surveys, such as geothermal exploration, hazardous liquid waste disposal, detection of underground explosions and geotechnical studies of groundwater seepage. It is also easy to summarize the risks of proceeding: at present we cannot demonstrate that the SP anomaly will be detectable, the usefulness of the result will depend strongly on the geology of a particular site, so that studies at one site may not transfer easily to another, and more
research is required before we know how to relate the observations to the flow field with any certainty, or before we can decide how much information about the flow field can be learned. In my opinion, the study of SP anomalies to monitor geothermal injection is the type of research which it is useful to pursue, because the results are uncertain but the possible pay-off is high.

If it is decided to proceed, an SP survey should be conducted in the vicinity of an injection well where the geology is known. Simple calculations based on the theoretical work described above could be used to pick a favorable site and to estimate the lateral extent of the anomaly at that site. Measurements should be made before, during and after injection in order to demonstrate that the SP anomaly can be seen. Reservoir engineering studies could help indicate how long a period of injection is required, and how often measurements should be taken. This survey could be performed at low cost as an additional task at an injection site where measurements were being taken to evaluate other methods. Once an injection-related anomaly has been detected, then theoretical studies should proceed to develop the methods for understanding the flow and thermal fields which caused it.
Figure VII-1. General model of the production of SP anomalies by coupled heat, mass, and current flow. This also illustrates the approach of Nourbehecht (1963) and Fitterman (1978).
Figure VII-2. A model of the production of SP anomalies from injection in which it is assumed that the electric potentials do not influence the heat and mass flow. This illustrates the approach followed by Sill.
Figure VII-3. Post-shot contour map of self-potential data near BILBY, (Scott, Carroll, and Cunningham, personal communication). Note the large circular negative anomaly near AARDVARK, shot over two years earlier.
Figure VII-4. Interpretation of electrical layering one week after BILBY (Scott, Carroll, and Cunningham, personal communication). Dashed lines indicate preferred layer interpretation, asterisks an alternate.
Figure VII-5. Models for the production of SP anomalies (from Nourbehecht, 1963).

(a) One layer over half space geometry for the thermoelectric case.

(b) Thermoelectric potential
\[ f_1(r) / [(C_1 - C_2) T_0] \] vs. \( \left( \frac{r}{d} \right) \)
VIII

RESISTIVITY AND INDUCED POLARIZATION
ANOMALIES ASSOCIATED WITH AN EXPANDING
BRINE FRONT

J. Hanson
L. Younker
Introduction

Surface electrical methods have been used for a long period of time as an aid to determining the depth of the water table. More recently these methods have been used to trace contaminated plumes associated with landfill sites and other waste disposal sites (Rogers and Kean, 1980; Stollar and Roux, 1975; Fink and Anlenbach, 1974; Cartwright and McComas, 1968). The approach has also been used for delineating saline water and fresh water zones (Roy and Elliott, 1980), and it has been used to monitor the boundary of the Broadlands Geothermal Field in New Zealand (Risk, 1974). Recently Wilt et al., (1980) and Wilt and Goldstein (1981) have reported on repeat resistivity surveys at the Cerro Prieto Geothermal Field. Their results indicate that resistivity variations with time are theoretically detectable by means of surface measurements. Their modeling results suggest that long term changes associated with cold-water influx, fault zone migrations and formation of a steam zone could be detected by precision dipole-dipole measurements if they affected a significant subsurface volume.

In this section we describe some preliminary work focused toward assessing the possible application of these approaches to the geothermal injection monitoring problem. We have developed a flexible computer code which will allow a variety of injection scenarios to be simulated and alternative measurement strategies to be evaluated.

Methods

The resistivity structure of the earth can be determined by placing four electrodes on the surface. Two of these are used to drive current within the
earth and the other two are used to measure the voltage developed by this current. A wide variety of electrode arrays have been used for measuring the earth resistivity. The dipole mapping method as described by Keller et al. (1975) has been shown to be effective for mapping lateral changes in resistivity beneath the area being surveyed. In this method, a current field is established by a relatively widely spaced pair of fixed source electrodes. The electric field around the source is then mapped with closely spaced receiver electrodes which are moved about the area of interest. In a project somewhat analogous to the injection monitoring project, Risk et al. (1970) have successfully mapped the lateral boundaries of a conductive region using this method. For representation the observed electric field values are converted to apparent resistively values (assuming a uniform earth). Ideally these values would represent the averaged properties of the earth beneath the measurement location. In practice, however, complicated current flow patterns exist and the relationship between subsurface structure and apparent resistivity may be difficult to interpret.

The induced polarization method involves measuring the slow decay of voltage in the ground following cessation of an excitation current pulse or low frequency variations of earth impedance. As in the case of d.c. resistivity methods, a variety of electrode configurations are possible. Roy and Elliot (1970) have recently shown that combined interpretation of resistivity and IP surveys can give better resolution of the subsurface than resistivity surveys alone.
Code Description

In order to evaluate the applicability of resistivity and IP measurements to the problem of monitoring injected brines, we developed a computer code which was used to estimate measured signal (resistivity or IP) given a hypothetical injection history. The code is based on the mathematical representation of a 3-D conductive body located within a conductive half-space. The conductive body (representing the mass of injected brine) and the half-space (representing the earth) can have arbitrary conductivities. Furthermore, the anomalous body can have arbitrary shape. Two current probes (a current source and sink) are allowed by the code, and each can be moved anywhere on or in the half-space independent of the other. The only restriction is that the current probes be moved along linear paths. The two potential probes can be moved on or in the half-space subject to the same restrictions. The primary reason for the flexibility in moving both current and potential probes was to test the relative sensitivity of surface-surface, surface-downhole, and downhole-downhole configurations.

Illustrative Examples - Surface Surveys

Figures VIII-1 - 6 give examples of calculated resistivity and induced polarization anomalies associated with an expanding brine front. The geometry of the modeled array is given in Figure VIII-1. The array has fixed current probes at the surface and moving potential probes. Figure VIII-2 shows the effect of an expanding brine front on the apparent resistivity for five different positions of the front. Figure labels A-E represent the different positions. The effect of the moving front is highlighted in Figures VIII-2a-2c in which the position of the injection front is denoted above the
The calculation was for a conductivity contrast
\[ K = \frac{\sigma_1 - \sigma}{\sigma_1 + \sigma} = -0.95. \]

This probably represents an extreme case for geothermal injection scenarios. Figure VIII-3 gives the apparent resistivity anomaly for four different conductivity contrasts. Figures VIII-4 and VIII-5 are similar to VIII-2 and 3 except that the induced polarization anomaly is plotted.

From these plots it is readily apparent that for the assumed geometry the size, depth, and parameter contrast of the anomalous region is too small for the surface surveys to be of much value. In Figure VIII-6 we investigate the effect of depth on the calculated anomalies. It is apparent that even for the rather extreme case of thickness/depth ratio of 0.4, adequate detection of the brine front is unlikely.

**Discussion**

Enhancement of the brine boundary resolution by using a baseline survey prior to injection is possible. When one considers target size, depth and parameter contrast, and couples this with the interpretational difficulties associated with an inhomogeneous region above the injection zone, adequate resolution of the brine front by surface surveys seems most unlikely. Brine movement to a shallower aquifer through fractures could in many cases be detected and these types of surveys may be useful for this application.
If the brine front is to be mapped away from the injection well by resistivity methods, some form of borehole measurement strategy is probably necessary. Theoretical studies have shown that moving the source and receiver into boreholes can significantly improve subsurface resolution (Merkel, 1970; Dobecki, 1980; Lytle, 1980). Some practical support for this type of survey has recently been provided (Tweeton, 1981). Field tests were conducted at an in-situ uranium leaching operation in Wyoming. In that study, well-to-well resistance dropped significantly when a leach solution replaced ground water. The ore zone was 80 meters deep and 3 meters thick. A circular pattern of wells, with injection wells on the periphery and a producing well in the center was established. As the leaching proceeded the intent was to measure the resistance between the center well and each of the injection wells. Practical problems prevented the completion of the intended measurement strategy (the current electrode in the center well was out of the water during pumping because drawdown was greater than expected). Resistance measurements between injection wells across the pattern spaced approximately 25 meters apart indicated the technique could be useful. Tweeton (1981) has suggested that measuring the resistance between a center producing well and corner injecting wells before injection and daily during injection could indicate whether leach solution is moving uniformly toward the center. Our code is presently being adapted to evaluate whether this type of borehole measurement strategy could be useful for geothermal injection monitoring. Application of this technique would obviously require non-conductive casing and instrumentation capable of withstanding geothermal conditions.
Recommendations

- Small target size, parameter contrast, and expected injection depths make surface electrical measurements unattractive possibilities for effective mapping of brine front movement from well.

- These techniques could be useful to detect encroachment into shallow aquifers at some distance from the well. The optimal location for these monitoring surveys could be determined by other approaches being considered in this study. This type of application has been well studied by E.P.A. and other organizations and needs little additional work.

- Moving the source and potential probe into boreholes has a possible application to injection monitoring. Future work should include an assessment of the practical feasibility of this approach in geothermal wells as well as more detailed computer simulations to optimize the current/potential probe configuration.
Figure VIII-1. Schematic diagram showing the array geometry and the geometry of the expanding brine front. Fixed current probes at the surface and a moving potential probe; potential probe spacing is 1; $\sigma_1$ is the conductivity in the half-space; $\sigma$ is the conductivity of the expanding brine front; R is radius of the brine front.
Figure VIII-2. Apparent resistivity of an expanding brine front for three values of $R$. Conductivity contrast $K = -0.95$. Position of brine front is highlighted above diagrams, and the corresponding calculated anomaly is darkened.
Figure VIII-3. Effect of conductivity contrast on apparent resistivity for four different values of K where: \[ K = \frac{\sigma_1 - \sigma}{\sigma_1 + \sigma} \]
Figure VIII-4. Induced polarization anomaly associated with an expanding front. Labels and geometry are the same as in Figure VIII-2.
Figure VIII-5. Effect of conductivity contrast on induced polarization.
Figure VIII-6. Effect of depth on apparent resistivity anomaly (a) and induced polarization anomaly (b). Geometry is the same as Figure VIII-1. Brine front radius is 3. Figure labels A-E correspond to $D = 0.5, 1, 2, 3,$ and 5.
APPLICATION OF BOREHOLE GRAVITY TO
GEOTHERMAL INJECTION PROGRAMS

J. R. Hearst
Introduction

Small variations in the vertical component of gravity ($g_v$) have been found to be of considerable use in geophysical exploration. The phenomenon of interest to conventional exploration geophysics is the variation of $g_v$ with position on the surface. Two-dimensional contour maps of this variation are usually prepared. The change in $g_v$ caused by a buried mass will, of course, be greatest directly above the mass, but will vary with the horizontal distance between the mass and the measuring point. This variation can be used to attempt to locate and describe the mass. Surface gravimetry is typically used to locate buried faults, domes, and other structures of interest to the exploration geophysicist, and a vast literature exists describing the method. For example, Isherwood (1977) has used surface gravity to investigate the depletion of a geothermal reservoir at the Geysers.

Borehole gravimetry is a fairly recent extension of surface gravimetry to the third dimension. The phenomenon of interest is the variation of $g_v$ with depth in the hole, which is influenced by both the vertical and lateral position of the buried mass. With the surface gravimeter, the lateral distance between the mass of interest and the instrument is changed, but with the borehole gravimeter, the vertical distance is changed instead. This permits a different look at the mass, and a somewhat different method of analysis.

Instrumentation

The most modern borehole gravimeters (made by LaCoste and Romberg) can be used in cased holes as small as 12.5-cm diameter. The hole may be tilted by as much as $14^\circ$, and pressure may be as high as 80 MPa. Temperature may not
exceed $120^\circ$ C. We have proposed construction of a high-temperature case (Baker, 1977) that could permit use of the gravimeter at temperatures as high as $200^\circ$ C. Figure IX-1 illustrates the general design of the case. A modern gravimeter is owned by the U. S. Geological survey and is available for outside use. There also is USGS interest in obtaining the high-temperature case.

The concept of the horizontal range of investigation of a borehole gravimeter is complex (Hearst, 1977). The simplest statement is that a gravimeter can resolve 4 tonnes at a horizontal range of 1 m, and 40000 tonnes at a horizontal range of 100 m.

**Data Analysis**

At the Nevada Test Site, there is often a need to choose between two or more proposed geologic cross-sections describing the subsurface structure near a planned test location. A computer program, BIFUR, has been written at LLNL to calculate the borehole gravity vs depth that would be caused by two-dimensional structures that can be described by such cross-sections (Hearst and Mckague, 1976). BIFUR also compares this calculated gravity to measured gravity and to a density log in the hole at the test location (Hearst, 1981). This enables us to determine which cross-section is most consistent with the measurements. Another computer program, MORIA has been written at LLNL to calculate the terrain corrections necessary to reduce borehole gravity data. The formulas in MORIA, with some modification, are now used routinely by all borehole gravity users (Hearst, 1968; Hearst et al., 1980).
Location of Brine Front

We are interested in detecting injection of brine into an aquifer. We would like to know the distance that the injected brine has traveled from the injection well. One possible method of measuring this distance is by using a borehole gravimeter to detect the change in bulk density, or "density contrast" between the injected fluid and the fluid originally present in the aquifer. If the porosity of the aquifer is \( \phi \) and the change in fluid density is \( \Delta \rho \), then the density contrast, \( C \), is \( \phi \Delta \rho \).

Consider a cylinder of thickness \( T \), density contrast \( C \), and radius \( R \), where \( R \) increases with time, because of injection. Figures IX-2 and IX-3 show the change in gravity, in milligals (mgal), as a function of \( R \), for \( \phi \Delta \rho = 0.01 \text{ g/cc} \) for \( T = 100 \text{ m} \) and \( 200 \text{ m} \) respectively. The change of gravity is shown at the top of the aquifer, a distance \( T \) above the top, and a distance 2.5 \( T \) above the top in each figure. For different values of \( \phi \Delta \rho \), the gravities shown should be multiplied by the ratio of the different value to 0.01.

A normal aquifer would likely have a porosity somewhere near 0.2, and a reasonable number for \( \Delta \rho \) is about 0.1. Therefore a plausible number for \( C \) is about 0.02, meaning that the gravity values shown in the figures would be multiplied by 2 for that aquifer. The borehole gravimeter discussed above can resolve changes in gravity of 0.02 mgal easily and 0.01 mgal with care, so the figures indicate that by use of the gravimeter at several heights above the aquifer at several times, one could follow the progress of this density contrast. Therefore it seems reasonable to conclude that a borehole gravimeter can be used to study the progress of injection fluid whose density is markedly different from that of the fluid in the aquifer.
Deposition around Injection Wells

Dissolved solids in brine may precipitate and clog the pores in the formation around a geothermal injection well; the resulting loss of permeability may render the well useless. When the pores are clogged, the bulk density will increase by an amount $\Delta \rho$. This change in bulk density can be observed by both a density log and a borehole gravimeter, but the gravimeter can sense the range to which density has been increased. We have calculated a typical case with the following parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>0.2</td>
</tr>
<tr>
<td>Fluid flow rate</td>
<td>0.04 m$^3$/s</td>
</tr>
<tr>
<td>Precipitant concentration</td>
<td>500 ppm (weight)</td>
</tr>
<tr>
<td>Fluid density</td>
<td>1.0 g/cm$^3$</td>
</tr>
<tr>
<td>Precipitant density</td>
<td>2.2 g/cm$^3$</td>
</tr>
</tbody>
</table>

For these parameters, we can calculate the radius at which pores will be clogged (assuming the clogging does not prevent increased clogging radius) as follows (Hearst et al., 1977):

<table>
<thead>
<tr>
<th>Aquifer thickness</th>
<th>Time</th>
<th>Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m</td>
<td>40 y</td>
<td>130 m*</td>
</tr>
<tr>
<td>10 m</td>
<td>4 wk</td>
<td>2 m*</td>
</tr>
<tr>
<td>10 m</td>
<td>2 y</td>
<td>9 m</td>
</tr>
<tr>
<td>10 m</td>
<td>40 y</td>
<td>41 m</td>
</tr>
<tr>
<td>100 m</td>
<td>2 y</td>
<td>3 m*</td>
</tr>
<tr>
<td>100 m</td>
<td>40 y</td>
<td>13 m</td>
</tr>
</tbody>
</table>

Figure IX-4 is an example of the gravity change that would be caused by deposition in a 10 m thick aquifer at different times. The radii marked
with an asterisk are the minimum conveniently detectable with a borehole
gravimeter (given the parameters above.) As time increases, we can obtain more
detail about precipitate distribution by observing the shape of the gravity
anomaly.

Compaction of an Aquifer around a Production Well

As water and steam are withdrawn from a geothermal reservoir, the
reservoir will in some cases become more compact from pore collapse as the
pore pressure drops. Compaction may result in eventual subsidence of the
ground surface, but it would be desirable to measure the actual compaction of
the reservoir before subsidence occurs. Borehole gravimetry may be a way to
measure compaction of the aquifer directly.

Consider an aquifer with porosity $\phi = 0.2$, and a difference between rock and
fluid density $\Delta \rho$ of 1.5 g/cm$^3$. For any aquifer thickness, a different
density change would be required to produce 1 m of compaction. The smaller the
required change, the more likely the compaction. Repeat measurements of
gravity at the same depths (presumably the original top and bottom of the
aquifer) would sense the density change and indicate the compaction. For any
thickness, $h$, there will be an uncertainty, $\Delta h$, in the measured compaction
(Hearst et al., 1977).

<table>
<thead>
<tr>
<th>Thickness $h$ (m)</th>
<th>10</th>
<th>30</th>
<th>100</th>
<th>300</th>
<th>1 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \rho$ for 1 m compaction</td>
<td>0.14</td>
<td>0.05</td>
<td>0.015</td>
<td>0.005</td>
<td>0.0075</td>
</tr>
<tr>
<td>$\Delta h$ in measurement</td>
<td>24 cm</td>
<td>37 cm</td>
<td>45 cm</td>
<td>45 cm</td>
<td>45 cm</td>
</tr>
</tbody>
</table>

In a thick reservoir, only a very small change in density is needed to be
detected, and in any reservoir we can observe a change of as little as 1 m.
For larger density changes, the compaction will be greater, and the relative
uncertainty smaller.
Summary and Recommendation:

There are several applications for borehole gravimetry in geothermal development:

1. Observation of motion of injected fluid;
2. Verification of deposition of solids around injection wells;
3. Observation of compaction of reservoirs.

We recommend that development of a high-temperature case for a borehole gravimeter be a high-priority item in a research budget.
Figure IX-1. Design of a High Temperature Case.
Figure IX-2. Change in gravity in milligals as a function of R for $\phi\Delta\rho = 0.01$ g/cc and $T = 100$ m.
Figure IX-3. Change in gravity in milligals as a function of $R$ for $\phi \Delta p = 0.01 \text{ g/cc}$ and $T = 200 \text{ m}$.
Figure IX-4. Vertical gravity above a 10m thick layer of deposited solids of density change 0.25 g/cm³. Different deposition times corresponding to different radii of deposition are shown.
AN EVALUATION OF THE POSSIBLE EFFECT
OF NATURAL FLOW RATES ON THE DEVELOPMENT
OF GEOTHERMAL FIELDS - SALTON SEA EXAMPLE

L. Younker
J. Hanson
P. Kasameyer
Introduction

The development of an injection program which meets environmental standards and promotes the efficient exploitation of the geothermal field requires not only a reliable monitoring scheme, but it also requires that all important field parameters which affect flow patterns be recognized and taken into account. The type and distribution of permeability around injecting and producing wells has, for example, long been recognized as an important factor which must be adequately characterized before confidence can be placed in predictions of reservoir models. Similarly major discrete fractures which could short circuit the path between injection and producing wells, if present, must be accounted for in the design of an injection program. In this note we call attention to one factor largely unrecognized which could similarly dramatically influence the path and rate of movement of injected fluids. The natural flow field can significantly affect the development of the geothermal field if the velocity of that flow is comparable to the velocities induced by production and injection. To illustrate we use the Salton Sea field as an example. Recent work funded by OBES has allowed us to estimate mass flow rates associated with the Salton Sea hydrothermal system. These flow rates are used as input to a field simulator in order to assess their possible impact. The results support the general contention that natural flow rates around a young geothermal system could be high enough to affect long-term development plans, and should be considered in the design of an injection program.

Determining Natural Flow Rates

The extensive data set available from the southeastern part of the Salton Sea Geothermal System provides an excellent base for developing a methodology
for understanding such complex hydrothermal systems. We have used the existing data base to develop a mathematical model of convective heat transfer away from an inferred heat source. Critical steps in our analysis have included:

(1) Detailed characterization of the geology of the field (Tewhey, 1977).
(2) Evaluation of the relationship between geologic characteristics and thermal features (Younker et al., 1980).
(3) Interpretation of natural flow patterns away from the heat source (Kasameyer and Younker, 1978).
(4) Development of an analytical model to describe heat transfer away from the heat source (Kasameyer et al., 1981).
(5) Application of the model to estimate the age (Kasameyer et al., 1980); estimate the recoverable resources (Younker and Kasameyer, 1978); and to make recommendations for future exploration plans (Younker et al., 1980).

For the Salton Sea Field, the tectonic setting and geophysical data suggest a zone of localized intrusion in the offset region between the Brawley fault and the San Andreas fault. Mafic and silicic dikes intrude to within one kilometer of the surface in this area, providing the source of heat for the Salton Sea Geothermal Field. Because of low vertical permeability, convection cells which have large-scale vertical motion are precluded. High horizontal permeability and demonstrated lateral continuity of reservoir sands promote lateral flow of fluid away from the zone of intrusion.

Two features of the temperature field put additional constraints on this conceptual model. First, uniform steady-state heat flow is observed in a
500-m thick thermal cap over an area of 30 to 40 km². This observation indicates that the fluid flow patterns and rate of heat delivery to the thermal cap in this area have not changed for a substantial period of time. Second, the periphery of the high heat-flow zone is abrupt and the thermal gradient in the cap increases significantly with depth as the hydrothermal zone is approached. These observations indicate that heat has been delivered to the periphery for a much shorter time than is required for conduction in the cap to come to steady-state equilibrium.

A model of horizontal fluid flow outward from a localized heat source produces thermal fields which match these observations. The model is simple enough that analytical results can be evaluated for a broad range of parameters. Mass flow rates for the system are estimated by minimizing the variance between the surface heat flow data and the model. Flow rates consistent with the field data range from 10 to 30 million cubic meters per year. For the geometry of the field these rates correspond to flow velocities on the order of 20 to 30 m/year across the field. These rates are consistent with theoretical flow rates calculated for fluid flow around intrusions, and are the same order of magnitude as postulated flow rates obtained through development of the field (Kasameyer and Younker, 1978).

**Exploitation of the Field - Effect of Natural Flow Rates**

A computer program has been written that calculates the isotherm distribution within a reservoir under an arbitrary injection and production well configuration (Hanson, 1978). In addition, the program calculates the length of time required for injected fluid to heat to a given temperature.
The reservoir model consists of a single, non-leaky, liquid-filled flat aquifer (or fracture) of constant thickness and porosity and bounded on both sides by impermeable rock. All wells fully penetrate the aquifer. The model assumes that instantaneous thermal equilibrium is obtained between the pore fluid and the rock matrix within the aquifer. Conductive transport in the rock bounding the aquifer is allowed in the direction normal to the aquifer. Thermal conduction and dispersion in the fluid are ignored and the temperature of the fluid is assumed to be isothermal across the width of the aquifer. The initial temperature of the water and rock in the aquifer and the bounding rock mass is $T_0$. At time $t = 0$, the temperature of the injected water is set equal to $T_{\text{inj}}$. The fluid velocity field is assumed stationary in time. The volume heat capacities of the fluid and rock matrix and the thermal conductivity and diffusivity of the rock mass bounding the aquifer are assumed to be constant.

In order to assess the possible impact of the natural flow on the development of the resource, three cases have been considered. Figure X-1 shows the isotherm distribution after 50 years of continuous flow. Magmamax 2 and 3 are injecting fluid of 30°C into an aquifer with an initial temperature of 200°C. Magmamax 1 and Woolsey are producing wells. Parameters used in the calculation are given in the figure. Figure X-2b uses the same parameters except that the natural flow of $\approx 25 \text{m/ year}$ is accounted for; Figure X-2c is identical to X-2b except that the producing and injecting wells are reversed.

A comparison of the 3 cases indicates that the natural flow could have a significant effect on the long-term efficient exploitation of this resource. This is particularly highlighted in case III in which the injection wells are preferentially placed in order to take advantage of the postulated natural flow.
Figure X-1. Isotherm distribution after 50 years of continuous flow; 1 = 500°C; 2 = 1000°C; * = 2000°C.
Parameters used in calculation are listed.
Figure X-2. Isotherm distribution after 50 years of continuous flow; 
1 = 500°C; 2 = 100°C; *= 200°C.

(a) Isotherm distribution assuming no natural flow (same as Figure X-1);
(b) Isotherm distribution using flow estimates of 25 m/yr NW-SE flow;
(c) Isotherm distribution using flow estimates for injection and producing wells reversed; producing wells protected from thermal breakthrough.
XI

OVERALL SUMMARY AND PROJECT STATUS

L. Younkier
The prime objective of this project is to evaluate the feasibility of using remote geophysical techniques to monitor the movement of injected brine. The ultimate goal is to develop a monitoring system including witness wells and geophysical measurements that indicates where injected brine is moving. Accurate determination of the path of the injected fluid would be useful for both environmental and reservoir development applications. An effective monitoring system would guard against potential ground water contamination and aid the efficient development of the reservoir.

Table XI-1 (A,B,C) indicates the four major approaches we are considering for further analysis this year. In the figure, we have identified the potential of the approach, projected applications, and questions to be resolved before the method could conceivably be used at a geothermal site. It is clear that there will never be a 'black box' capability for accurately monitoring the precise location of the injected fluid, nor equally operational at all geothermal sites. There are, however, several approaches which under the right field circumstances could supply useful information. The techniques we are presently considering cover a range of possible applications. Obviously, there are many tradeoffs to be considered between cost, and 'quality' and completeness of the data.

Microseismicity. Recording small magnitude seismic events has the potential to provide a gross 3-D map of the pressure distribution surrounding an injection well. If this information is coupled with additional information on the type and distribution of permeability, it could be very useful for selecting and refining reservoir models. The appeal of this approach is that it could provide a relatively cheap 'reservoir map'. The disadvantages are that the information will be relatively imprecise.
Streaming Potential. Self-potential anomalies produced by moving fluid around an injection well could provide information regarding preferred flow directions. This information would be useful for refining reservoir models and locating monitor wells. The recently developed theoretical base makes this an attractive approach to consider. The appeal of this method if it proves feasible is that it could be a relatively inexpensive method to obtain information on flow pathways. The disadvantages are again that it will be a relatively imprecise map of the fluid movement.

Geotomography. Our preliminary analysis indicated that changes in electrical properties and seismic properties might be sufficient in some injection scenarios to allow imaging of a region between two boreholes via geotomography. The appeal of this approach is that given the right borehole configuration, a detailed image of the flow pathways might be achieved. Even in those cases where the injected fluid and the formation fluid do not have sufficient contrasts to allow detection, a carefully controlled geotomography experiment using salt tracers could supply valuable information about detailed flow pathways useful for selecting and refining reservoir models.

Tidal Response. Careful measurement and interpretation of pore pressure response to solid earth tides has the possibility of identifying the nature and orientation of the primary fluid conduits away from the injection well. This information would be useful for choosing a flow model for the injection zone and for identifying possible preferred flow directions. The appeal of this approach is that, unlike conventional well testing, pumping is not required, thereby, allowing for reliable and cost effective long term data acquisition. The target parameters for tidal reservoir testing are the same as conventional testing—namely, the fluid conductivity and reservoir
capacity (storage). However, because of the tensorial nature of the driving force (tidal strain), the spatial orientation of the preferred flow conduits will be manifested in the well pressure record. This observation has been confirmed by work carried out by LLNL at Raft River, Idaho in 1980 and by recent work by Energy, Mines, and Resources, Canada.

Obviously, if these approaches are established as feasible, they would simply become part of the tools available to the reservoir engineer. They would be used in conjunction with other established methods such as tracer studies and conventional well tests. We have, in part, selected these techniques because we believe they add a new dimension to the existing monitoring capabilities.

In addition to the approaches considered in Table XI-1, several other techniques could make valuable contributions to an overall monitoring program. These include borehole gravity, borehole resistivity, cross borehole seismic probing, and measurement of tilt and strain. In the case of borehole gravity the critical issue to be resolved is the development of a high temperature case which would permit operation at higher temperatures. If developed, borehole gravity measurements could probably be used to monitor deposition around injection wells and compaction of the aquifer associated with production. Borehole resistivity and cross borehole seismic probing need to be investigated more fully, both with regard to practical considerations and scientific feasibility. Winkler and Nur (1982) have recently shown the effects of pore fluids on seismic attenuation. Their results suggest the cross borehole seismic 'geotomography' might be a useful approach to consider in more detail. Helm (1981) outlined an approach for evaluating whether pore
pressure induced elastic strain and tilt measurements would be a useful approach for monitoring fluid movement. Because of the complications associated with unfolding the coupled elastic-thermal fluid flow problem, we have chosen not to pursue this approach at this time.

It is clear that many of the approaches considered so far would benefit from borehole placement of instruments. A fundamental issue to be resolved is whether instrumentation compatible with the borehole environment can be efficiently developed and deployed in geothermal situations.

In Figure XI-1, we provide an overview of a monitoring scheme that incorporates existing techniques with those under investigation in this study. In a normal operation, reservoir developers would rely largely on conventional well tests to develop and evaluate a reservoir model. Tracer studies could be used as a follow-up test of the ability of the model to accurately predict the path of injected fluid. The four approaches under consideration could provide considerably more detail and result in improved understanding of the reservoir. This information could be used to refine the reservoir model as well as locate positions where additional monitoring wells would be most useful.
Table XI-1A. Alternative monitoring approaches under consideration.

<table>
<thead>
<tr>
<th>MONITORING APPROACH</th>
<th>DESCRIPTION</th>
<th>POTENTIAL OF APPROACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>MICROSEISMICITY</td>
<td>Use a small seismic net to record and locate small magnitude events associated with injection</td>
<td>Provide a map of portion of reservoir above some 'critical' pressure and follow temporal evolution</td>
</tr>
<tr>
<td>STREAMING POTENTIAL</td>
<td>Record self potential anomalies produced by moving fluid in an inhomogeneous medium</td>
<td>Identify gross direction of fluid flow</td>
</tr>
<tr>
<td>CROSS BOREHOLE GEOTOMOGRAPHY</td>
<td>Generate a two dimensional image of area between two boreholes using electromagnetic wave propagation or seismic waves</td>
<td>High resolution image of flow pathways around injection well</td>
</tr>
<tr>
<td>WELL PRESSURE RESPONSE TO TIDES</td>
<td>Measure pore pressure response to solid earth tides</td>
<td>Discrimination between fracture and pore porosity in primary fluid conduits and estimate of mean spatial orientation of fluid carrying fractures</td>
</tr>
</tbody>
</table>
Table XI-1B. Projected applications of the approaches.

<table>
<thead>
<tr>
<th>MONITORING APPROACH</th>
<th>PROJECTED APPLICATION OF APPROACH IN INJECTION MONITORING</th>
</tr>
</thead>
<tbody>
<tr>
<td>MICROSEISMICITY</td>
<td>Pressure 'map' useful for selecting and refining reservoir models and locating monitor wells</td>
</tr>
<tr>
<td>STREAMING POTENTIAL</td>
<td>Indication of preferred flow directions useful for refining reservoir models and locating monitor wells</td>
</tr>
<tr>
<td>CROSS BOREHOLE GEOTOMOGRAPHY</td>
<td>High frequency-short spacing application will allow detailed observations of fluid movement useful for selecting and refining reservoir models; Low frequency-longer spacing will allow gross movement to be monitored</td>
</tr>
<tr>
<td>WELL PRESSURE RESPONSE TO TIDES</td>
<td>Identification of flow model appropriate for injection zone Provide information on preferred flow pathways away from well</td>
</tr>
</tbody>
</table>
Table XI-1C. Questions to be resolved by future work before approach can be applied.

<table>
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<tr>
<th>MONITORING APPROACH</th>
<th>QUESTIONS TO BE RESOLVED BY FUTURE WORK</th>
</tr>
</thead>
<tbody>
<tr>
<td>MICROSEISMICITY</td>
<td>*Can seismic events associated with injection be detected and located with sufficient precision?</td>
</tr>
<tr>
<td></td>
<td>*What is the relationship between this 'reservoir map' and flow patterns?</td>
</tr>
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<td></td>
<td>*Can an easily deployed system be developed?</td>
</tr>
<tr>
<td>STREAMING POTENTIAL</td>
<td>*What is the magnitude of anomalies associated with injection?</td>
</tr>
<tr>
<td></td>
<td>*Under what circumstances might we expect anomalies big enough for detection?</td>
</tr>
<tr>
<td></td>
<td>*Can anomalies be interpreted with enough detail to be useful?</td>
</tr>
<tr>
<td>CROSS BOREHOLE GEOTOMOGRAPHY</td>
<td>*What physical contrasts are required for adequate detection?</td>
</tr>
<tr>
<td></td>
<td>*What is the scale of operation of the technique?</td>
</tr>
<tr>
<td></td>
<td>*How easily can the technique be deployed?</td>
</tr>
<tr>
<td>WELL PRESSURE RESPONSE TO TIDES</td>
<td>*Under what circumstances can the tidal signal be separated out from other pressure perturbations?</td>
</tr>
<tr>
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<td>*What types of systems are suitable for this analysis?</td>
</tr>
<tr>
<td></td>
<td>*Can a multi-well system be evaluated simultaneously?</td>
</tr>
</tbody>
</table>
Fig. XI-1. Overall monitoring methodology including existing techniques and approaches under investigation. Asterisks denote types of information potentially available from each technique.
Acknowledgements

The authors wish to express their appreciation to K. Young and B. Ellison for their help in preparing and assembling this document and to D. Tatman for help in preparing the graphics. We also thank the Nuclear System Safety Program Office for its support, particularly L. Cleland and J. Johnson, and J. Katz from the DOE-San Francisco Operations Office.
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