Proceedings of the

GEOTHERMAL PROGRAM REVIEW VII

"DOE Research and Development
for the

Geothermal Marketplace"

March 21-23, 1989
San Francisco, CA

Coordinated by:

Meridian Corporation
Alexandria, VA 22302

Sponsored by:

U.S. Department of Energy
Assistant Secretary, Conservation and Renewable Energy
Geothermal Technology Division
Washington, D.C. 20585

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
Progress in research and development of four of UURI's projects are reviewed in this paper. First, the development of chemical tracers has evolved to a field test in the Dixie Valley geothermal system in Nevada. Second, the measurement of in situ stress continues to demonstrate changes with location in the orientation of stress within active geothermal systems. Third, we continue to develop hydrologic models of geothermal systems based upon fluid inclusion measurements. Fourth, we are developing equipment that will allow testing of borehole to borehole and borehole to surface electrical resistivity techniques for locating fluid-filled fractures.

In most geothermal fields, the spent, cooled, brines must be injected back into the formations. The purposes of injection are to avoid surface and culinary water pollution and to maintain reservoir pressures. However, injection can lower the temperature of the produced fluids in a field by mixing with the hotter formation fluids. In order to mitigate this problem, the subsurface paths of the injected fluids must be known. Tracers can be used to label and track fluid movement and monitor chemical changes of the injected fluid. At the inception of this project, very few tracers were available to track the liquid phase, only one to track the vapor phase (tritium), and none to quantify the transformation of liquid to vapor. Of those that were available for tracing the liquid phase, little was known about their stabilities or behaviors at the elevated temperatures that typify resources capable of electric power generation.

During the past few years, the University of Utah Research Institute has been involved in the development and testing of several organic anions for use as geothermal tracers. Our prior accomplishments include identification and testing of 39 acid anion compounds and fluorescein dye at temperatures up to 300 deg C and times up to 4 weeks. Of these, 24 look promising at 200-deg C, 15 at 250 deg C, and 5 at 300 deg C. These are the methylbenzoic acids, the benzenesulfonates, the benzene-dicarboxylates, and benzoic acid itself. The compounds that are the least stable at high temperatures are the fluorinated and trifluoromethylated benzoic and phenylacetic acids. Ironically, these are the best low-temperature groundwater tracers because they resist biodegradation. Although biodegradation may be a problem for the tracers that we have developed, it should occur only in the sample bottles. Preservatives are used when the tagged fluids are sampled. We are currently performing experiments to determine what preservatives are best. In our experiments we use sodium azide, but formaldehyde may be feasible. Formaldehyde would be preferable since sodium azide must be used with care because of safety considerations due to its high chemical reactivity.

The objective of the DOE-sponsored research at UURI is to reduce industry cost and risk in geothermal exploration and development. In order to do this we have established a multi-faceted program that utilizes advances in the fields of geology, geochemistry, and geophysics.
with have detection limits of approximately 5 ppb, and we are currently working on lowering them to the ppt range. We have also shown that all of the organic compounds decay rapidly when exposed to oxygen, as would be the case when they are injected with oxygenated groundwater into a geothermal system. We have developed the analytic methodology for simultaneously analyzing several organic tracers on a high-pressure liquid chromatograph (HPLC), and have developed experimental laboratory techniques for testing tracers without oxygen contamination and in the presence of rocks.

An injection test involving several of our candidate tracers was performed at the Dixie Valley geothermal field during the winter of 1988-89. The test was a cooperative effort between DOE and Oxbow Geothermal, the operators of the Dixie Valley field. Electric power production at Dixie Valley began during the summer of 1988 from a wellfield consisting of six production wells and four injection wells. The Dixie Valley field was chosen because the reservoir model of the field (based on MULKOM; Pruess, 1983) predicted relatively rapid breakthrough of injected fluids from some of the injection wells to the production wells. Prediction of rapid breakthrough and the existence of a detailed reservoir model indicated that both tracers and the predictive capacity of the model could be simultaneously tested.

Tracer slugs were inserted into three of the injection wells. Each slug was prepared in a frac tank containing 300 bbls of flashed geothermal brine, and then pumped into the well. Benzenesulfonate (300 kg) was injected into well 45-5, fluorescein (150 kg) and benzoate (100 kg) were injected into well 32-18, and fluorescein (50 kg) and 4-ethylbenzenesulfonate were injected into well 52-18.

The tracer test at Dixie Valley was innovative in several respects. Multiple tracers were used for the first time in a major multi-well tracer test. One of the tracers in each set, fluorescein, was used because it is detectable in the field at concentrations as low as 3 ppb. This enabled the return curve to be determined in the field, guiding the frequency of sampling and laboratory analysis. The other tracer in each set was a very stable organic compound that had to be analyzed in the laboratory. Because fluorescein displays slow thermal degradation at the Dixie Valley reservoir temperature, the ratio of fluorescein to the more stable tracer indicated an average temperature along the breakthrough path. These calculations depend on kinetic data for fluorescein decay developed last year by UURI. The return curve for the injection breakthrough can be produced by either the fluorescein data, corrected for thermal decay, or by the concentrations of the more stable tracers. Each well was tagged with a unique set of tracers, enabling the source of breakthrough to be traced.

Automatic samplers were used to obtain samples from the production wells. The samplers were built by UURI based on a prototype constructed by Roland Horne. These instruments use commercial microprocessors and automatic valves and they are powered by car batteries. Manual sampling would have required at least three persons on the site at all times for the duration of the test period, which was two months. By using the automatic samplers only one person was required on site during the test. In addition, the samplers were programmed to run hot brine through the tubing every few seconds, avoiding freezing of the sampling lines that would have created problems even for manual sampling.

To date, one production well, well 76-7, has shown breakthrough. The presence of benzoate along with fluorescein in the fluid from well 76-7 indicates that breakthrough is from injection well 32-18. Laboratory analysis, which is slower but more accurate than field analysis, will determine whether tracers are present in fluid from the other production wells. Concentration of the fluorescein in the fluid from well 76-7 plotted against time is shown in Figure 1. The actual data are shown in this figure along with the concentration of fluorescein corrected for thermal decay assuming an average fluid path temperature of 240 deg C. Preliminary analyses of benzoate indicates that this is a reasonable average temperature. More analyses of benzoate will refine the estimate of average temperature.

![Figure 1 - Dixie Valley tracer return curve](image-url)
STRESS ANALYSIS OF GEOTHERMAL RESERVOIRS

There are a number of techniques for determining the orientation of the principal horizontal stresses in a well bore. We have been investigating the use of the dipmeter log and have reported some of the findings previously (Allison and Nielson, 1988). Through this past year, additional data have continued to support conclusions that the stress orientation in geothermal systems may differ from the regional stress, that the stress orientation may change dramatically through a field or even within a borehole, and that the change in stress orientation often occurs across a fault.

We believe that the mapping of the stress in a geothermal reservoir will prove to be of value in the exploration and development of that reservoir. The stress data should be analyzed in the context of structural mapping of the reservoir that shows the location and orientation of faulting and fracturing and hopefully the relative age relationships of these features. It has been found that faults that host geothermal fluids are not always compatible with the present stress environment (Nielson et al., 1988). Older faults formed under a stress environment different from the presently existing one can respond to the present stress environment by being either open and permeable or closed. There are numerous examples where the stress orientation within the geothermal system is distinctly different from the regional stress environment. This conclusion is also supported by analysis of seismic data.

When it can be shown that the faults and fractures hosting the geothermal fluids are compatible with the measured stress orientation, this becomes a powerful tool for the exploration and development of geothermal systems. Some applications are outlined below.

Hidden systems: As drilling explores deeper levels of the crust, it has been found that prospective fractures are commonly not represented at the surface, often because of younger volcanic cover. Most efficient use of the drill would dictate a directional drilling plan whereby the well is deviated in a direction perpendicular to the prevailing fracture trend, which in extensional environments parallels the least horizontal principal stress. This direction can be determined through the analysis of breakouts. This strategy increases the probability of intersecting geothermal production.

Stimulation: Fracture stimulation has been extensively used in Japan to increase permeability in hydrothermal systems and is an integral part of the development of hot dry rock reservoirs. Our analysis of a fracturing experiment at the Baca geothermal system in New Mexico demonstrates that the induced fracturing was confined to a fault-bounded structural block with a specific stress orientation. The fractures propagated were parallel to the least principal stress, as would be predicted. We conclude that a documentation of the in situ stress orientation is necessary to plan the location for a fracturing attempt.

Injection: The location for brine injection should be determined based on the objective of the process. Again, determination of the in situ stress could be critical in being able to predict the route taken by the injected fluid. If fluid is injected into a structural block that is totally separated from the producing fractures, it is unlikely that a goal of pressure maintenance will be achieved. However, this action would be appropriate for purposes of permanent disposal of waste fluids.

UURU is working to transfer this technology to industry. In addition to papers at several conferences, we have established a Dipmeter Research Center. This center will be concerned with research into all aspects of the dipmeter log, including the analysis of borehole breakouts as indicators of in situ stress.

HYDROLOGIC MODELING OF GEOTHERMAL RESERVOIRS

Detailed hydrogeochemical models of geothermal reservoirs are needed to locate production and injection wells and to numerically predict the effects of long-term production. In order for these models to be useful, they must describe the temperature, salinity and gas distributions within the reservoir, the interactions between reservoir fluids, the extent of boiling and mixing and the direction of fluid movement through the geothermal system. Because of the drilling and completion techniques currently in use, fluid samples can generally only be collected from the production zones. This data provides only a partial view of the reservoir.

During the past year, we have examined the application of fluid inclusion data studies to the development of detailed fluid-flow models of geothermal systems. Fluid inclusions are fluid-filled, micron-size cavities that form in hydrothermal minerals during mineral growth or subsequent fracturing. Because secondary minerals are found throughout the reservoir, and are unaffected by the drilling processes, fluid inclusions in them can provide samples of the geothermal fluids from portions of the reservoir where no produced fluid can be sampled.

33
Fluid inclusions are presently being studied from the high-temperature systems at Coso, California, and Los Azufres, Mexico, and the moderate temperature system at Heber, California. In all three systems, fluid-inclusion temperatures and salinities have been found to correspond closely to the downhole measurements and compositions of the production fluids. These relationships demonstrate that data from the inclusions can be used to help model the present thermal systems.

The integration of fluid-inclusion data with chemical analyses of the production fluids to characterize fluid flow is well illustrated by the study at Coso. Figure 2 (Moore et al., 1989) summarizes measurements made on 1200 inclusions from 12 production and gradient wells. For comparison, the composition of the production fluids is also shown. Tm values refer to the melting temperature of ice in the inclusions, which can be converted to an apparent salinity. Variations in Tm can also provide information on the CO₂ contents of the inclusion fluids. Computer programs have been written to calculate the CO₂ contents and salinities from the fluid inclusion data.

Figure 2 demonstrates that the reservoir at Coso consists of a plume of hot water that originates in the southern part of the field. The least diluted samples of the plume are contained in fluid inclusions from a depth of 1800 m in well 72-19. Fluid-inclusion measurements show that this fluid has a temperature of 322 deg C, a salinity of 1.4 equivalent weight percent NaCl, and a CO₂ content up to 2.4 weight percent. As the plume moves laterally to the north and east it is diluted by low-chloride waters with temperatures near 130 deg C. Significant boiling occurs at shallow depths in the northern part of the field as indicated by the large variation in Tm values shown in Figure 2. An important consequence of this boiling has been the enrichment of the shallow groundwaters in CO₂. More extensive CO₂ enrichments have been documented at Los Azufres from fluid inclusion data. The recognition of these enrichments is important because they affect both the production and scaling characteristics of the wells and the geophysical responses of the altered rocks within the reservoir.

CROSS-BOREHOLE ELECTRICAL TECHNIQUES

The primary advance in borehole electrical geophysics at UURI in 1988 was in development of computer modeling algorithms. Two inversion algorithms were completed which construct two-dimensional estimates of the in-situ electrical resistivity from cross-borehole, borehole-to-surface, or surface-to-borehole direct current electrical potential measurements. One algorithm calculates the response of an arbitrary two-dimensional earth using the finite element method. This algorithm uses a fixed discretization of triangular subregions, and resistivities of selected subregions are allowed to vary using least-squares inversion techniques to adjust the earth to optimally match the electrical potential data. The other algorithm is based on an integral equation approach and provides capability to model discrete bodies in a half space. What makes this second algorithm unique is that both resistivities of the bodies and their boundary locations are treated as parameters which are solved for using least squares inversion techniques. These algorithms are apparently unique in their respective capabilities, both for the accuracy of the calculation of responses and for their automated interpretation capabilities. The algorithms have many potential applications in geothermal reservoir engineering, including fracture system detection, mapping steam and alteration zones, and monitoring the flow of injection fluids.

We attempted to apply the above algorithms to two data sets, one from a mining environment, and one from a coal environment, which were collected with industry equipment and support in 1987.
Unfortunately, data quality was too poor to allow meaningful interpretation. We were successful, however, in carrying out a number of modeling studies aimed at assessing resolution of cross-borehole resistivity methods when applied to monitoring the flow of injection fluids. Our modeling results indicate potential for success in application of the methods to monitoring problems. We began planning in 1988 to develop our own equipment to carry out borehole electrical measurements in anticipation of acquiring meaningful data sets to verify the utility of cross-borehole, borehole-to-surface, and surface-to-borehole electrical measurements with field tests. Thus equipment will be field operational in FY89.

REFERENCES


