GEOPHYSICAL MEASUREMENT OF GEOTHERMAL FLUID PRODUCTION AND INJECTION

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Geophysical Measurement of Geothermal Fluid Production and Injection
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Geothermal operators use complex reservoir engineering models to design their well fields and production/injection strategies and to predict the performance of their reservoirs. Collection of in-situ data for input and validation of these models in wells is expensive, and geophysical measurements from the surface or remotely at some distance from boreholes can be cost effective. The Hydrothermal Research Program of DOE is developing techniques to track injected fluid and to monitor the effects of production and injection geothermal fields using geophysical means.

INTRODUCTION
Reservoir engineering models are used to predict the future performance of geothermal fields in order to make decisions about well placement and production strategy. Information about the response of a geothermal field to production and injection is required in order to validate the applicability of these models to that field. For this purpose, information, typically temperature, pressure and fluid samples, is routinely collected in monitoring and production wells. Wells can provide very precise information from specific locations in the geothermal field, but they are expensive, and measurement and sampling problems due to high temperatures and flashing can reduce the value of the information obtained in them. Geophysical monitoring of changes in the geothermal field can be used to supplement traditional monitoring methods and provide additional constraints for validating geothermal model applications.

VALUE OF GEOPHYSICAL MONITORING
Changes in physical properties at depth can be measured using geophysical methods with sensors on the surface or in remote boreholes. Changes in physical properties may be associated with the movement of pressure, chemical and thermal fronts through the geothermal reservoir. These changes may be direct, such as a change in electrical resistivity caused by a change in pore fluid salinity or temperature. Alternatively, the detectable change might be related to a more complex phenomenon, such as increasing micro-seismicity as the pore pressure reaches a critical value. Geophysical monitoring has three advantages compared to using data from monitoring wells. First, a large volume of the reservoir can be studied from the surface or from a few wells, lowering monitoring costs. Second, geophysical measurements integrate properties over larger volumes, providing average values that can be appropriately compared to model results. Finally, geophysical instrumentation may not be exposed to the hot corrosive conditions in monitoring wells, making more types of measurement possible.

LIMITATIONS OF GEOPHYSICS
Geophysical monitoring has different limitations than monitoring wells. First, the usefulness of a specific geophysical method differs significantly from site to site, and with production/injection strategy. This variation comes both from the question of what physical property changes will occur within the reservoir, and the question of how well those changes can be detected in a given location. A second limitation comes from ambiguity in the interpretation of a geophysical anomaly once it is detected. There are two levels of ambiguity, uncertainty about where the changed physical properties actually occur, and uncertainty about how they should be translated into relevant reservoir information. The first level of ambiguity is reduced significantly in our application, where repeated measurements are used to eliminate geological variability. Because of these ambiguities, geophysical methods are best used to supplement and extrapolate accurate single point measurements from observation wells.

The DOE program is designed to increase the usefulness of geophysical monitoring by identifying methods that do or could work, and by reducing the importance of the limitations described above. The limitations are being dealt with by collecting case histories and improving measurement and interpretation methods for geophysical methods. Work relevant to geophysical monitoring is taking place at three organizations, Lawrence Berkeley Laboratory (LBL), University of Utah Research Institute (UURI), and Lawrence Livermore National Laboratory (LLNL). These efforts will make it possible to predict whether geophysical methods will be useful in specific cases, and to increase the number of times when the answer is yes.

GEOPHYSICAL METHODS ARE USEFUL

Some geothermal methods have been successfully used to monitor and understand changes in geothermal reservoirs. Density and resistivity changes within reservoirs can be predicted with confidence, and their measurement is routine and well understood. A very useful application of surface gravity measurements has recently been published by Atkinson and his colleagues at UNOCAL Geothermal. Over several years, they have used repeated surface gravity surveys over a geothermal field to measure the
total mass loss in the field, and to determine which areas in the field are losing mass the fastest. They require the recharge parameters in their numerical simulations be adjusted to produce the observed values of mass loss, which are uniquely determined by the changes in the gravity field with time. This information has been incorporated into models for several years, and is obviously considered to be cost effective. This proven method could be applied effectively at many geothermal fields, and supplemented by repeated borehole gravity surveys, which work in cased holes, in order to constrain the depth where the mass loss is occurring. Repeated surface resistivity measurements have also been used by the LBL group to estimate the amount of fresh water recharge at Cerro Prieto. Like gravity, this routine method should be useful at those geothermal fields where there are large variations in fluid salinity, and can be routinely extended to borehole measurements. The DoE program will continue to publicize successes in order to promote the use of geophysical methods for monitoring.

DOE WORK DEVELOPING NEW METHODS TO PREDICT AND INTERPRET GEOPHYSICAL DATA

DoE is supporting a number of efforts to develop and improve techniques to allow us to predict the geophysical signature produced when reservoir properties change. These efforts concentrate on improving the prediction and interpretation of anomalies in those techniques known to be useful: gravity and resistivity. Two approaches are being taken. The first is to develop improved methods to interpret the signals caused by 3-dimensional anomalous bodies. UURI is developing codes for the 3-dimensional interpretation of DC and EM resistivity, and LBL is studying the application of 3-dimensional codes to gravity interpretation. The second approach, followed by both LBL and UURI, is to calculate the downhole and cross-borehole resistivity anomalies for a variety of geometries, in order to evaluate the best method for collecting this type of data. These studies are useful to the reservoir characterization and fracture detection efforts, as well as to the geophysical monitoring project.

DOE CASE STUDIES

There are several geophysical signals that would be useful for understanding processes if we could predict their occurrence or understand fully their causes. Examples include electrical self-potentials and micro-seismicity. Electrical self-potentials are natural DC signals, that are caused by a combination of pressure gradients, fluid chemistry gradients, and thermal gradients. If we understood these signals, we could gain information about the pressure, fluid and thermal fronts in the reservoir. Unfortunately, we do not understand the characteristics of the reservoir rocks that give rise to these signals. We are collecting case studies of changes in SP signals as a reservoir is produced in order to determine if these anomalies are common, and to develop a database to stimulate theoretical and laboratory studies of electrical self-potential. These studies include surveys collected by LBL before and after start-up of the Mammoth-Pacific Power Plant, in Mammoth Lakes, California, and a recent re-survey of the self-potential around the East Mesa power plant, conducted by LBL.

Micro-seismicity is known to occur when injection raises pore pressure above a critical level, and unexplained events have been seen at several sites. In addition, seismicity is detected around production wells at the Geysers. In order to better understand the many factors that produced induced seismic signals in geothermal fields, DoE is supporting a number of case studies where micro-seismicity is being collected in well-characterized reservoirs. LNL is completing a study at the Mammoth-Pacific plant, and is planning to monitor seismic activity during the production/injection test of the Salton Sea Scientific Drilling Project well in June, 1988. With support from the Geothermal Technology Organization, LBL is starting a detailed monitoring program at the Geysers. These studies have the additional benefit of observing waves from natural earthquakes. These waves provide an additional source of energy used to characterize the reservoir and observe changes in the system.

DOE STUDIES DEVELOPING NEW GEOPHYSICAL METHODS

DoE is supporting a number of studies to develop advanced geophysical methods that will be useful for geophysical monitoring. LBL has developed a multiple-electrode resistivity system for rapidly collecting borehole-to-surface electrical data as a function of azimuth about an injection or production well, and has developed a shear-wave vertical seismic profiling system that could be used to look for changes in the ratio of compressional and shear wave velocities around a well. LNL has produced seismic attenuation images of the Medicine Lake Volcano area, which, when combined with velocity data, are interpreted to indicate zones of dry and saturated rock. Each of these methods could be repeated to detect and understand the changes in a reservoir. In addition, LNL is testing array processing method to locate continuous seismic noise generated by production and injection.

SUMMARY

The DoE program is designed to increase the amount of information available to validate reservoir models by developing and demonstrating geophysical methods for monitoring changes in geothermal fields. This program has three components: development of improved modeling and prediction capability for a number of techniques, the collection and dissemination of case studies to increase our understanding of the
circumstances which make each technique useful, and the development of advanced techniques for geophysical monitoring. The value of the program will come as industry is encouraged to use geophysical monitoring methods, which can be a cost-effective means for gathering information about reservoir response.

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