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The Coso Geothermal Area:
A Laboratory for Advanced MEQ Studies for Geothermal Monitoring

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ABSTRACT

The permanent 16-station network of three-component digital seismometers at the Coso geothermal area, California, supplemented by 14 temporary instruments deployed in connection with the DOE Enhanced Geothermal Systems (EGS) Project, provides high-quality microearthquake (MEQ) recordings that are well suited to monitoring a producing geothermal area. We are currently using these data to investigate structure and active processes within the geothermal reservoir by applying three advanced methods: a) high-precision MEQ hypocenter location; b) time-dependent tomography; c) complete (moment tensor) MEQ source mechanism determination. Preliminary results to date resolve seismogenic structures in the producing field more clearly than is possible with conventional earthquake-location techniques. A shallow part of the producing field shows clear changes in the ratio of the seismic wave speeds, V_p/V_s, between 1996 and 2002, which are probably related to physical changes in the reservoir caused by fluid extraction.

Introduction

The Coso geothermal area is one of the best seismically-monitored producing geothermal area in the world. Since the early 1990s, the U.S. Navy has operated a network of 18 three-component digital borehole seismometers at Coso, 13 of them within or near the producing field, to monitor microearthquakes (MEQs) (Alvarez, 1992). Data digitized in the field are transmitted to a central site where the Navy detects MEQs and determines hypocentral locations. The geothermal area is seismically highly active, with 10 to 15 earthquakes per day typically. Many of these are well distributed throughout the geothermal area, though large numbers of regional earthquakes also occur, related to tectonic activity of the southern Owens Valley.

At most geothermal fields, only sparse networks of vertical-component seismometers monitor MEQ activity, using analog telemetry and recording methods. A dense modern network like that at Coso, which gathers a rich set of high-quality digital seismograms, opens up the possibility of applying a new generation of data-processing techniques to study the field and its response to production-related activities. Such work is underway at Coso as part of a U.S. Geological Survey – U.S. Navy – DOE collaboration. This project involves processing data gathered by both the permanent U.S. Navy network and a temporary network deployed to increase station coverage in near fluid injection experiments of the Coso Enhanced Geothermal Systems (EGS) Project (Rose and others, 2003; Rose and others, 2002). A significant part of the work involves extending, developing and optimizing software for application to geothermal targets.

Methodology

We are developing and applying three primary data-processing methods:

High-resolution hypocenter location — Traditionally, earthquakes are located individually, by fitting the arrival times of seismic waves at many seismometers. This method is subject to strong biases caused by wave-propagation effects in the unknown three-dimensional structure in the Earth. Recently developed methods greatly reduce this bias by fitting arrival-time differences and locating earthquakes relative to one another. Such methods yield accurate relative locations of nearby earthquakes, though they do not substantially improve absolute locations. A further substantial improvement, made by Waldhauser and Ellsworth (2000) involves simultaneously locating up to thousands of earthquakes simultaneously, and reduces the effects of random observational errors by an order of magnitude. Application of this method at other geothermal areas has demonstrated its usefulness in resolving seismically active geological structures (Foulger and others, 2004).

Figure 1 shows preliminary results of applying both kinds of methods to MEQs at Coso, using data from the permanent seismometer network recorded during injection experiments in September of 2003. The Waldhauser-Ellsworth locations resolve MEQ clusters near injection wells, as well as small northeast-southwest features in the general seismicity, much better than single-event locations do. Figure 1 is based on inverting differences of measured arrival times. It is possible to obtain much greater accuracy by measuring arrival-time differences directly, using waveform cross-correlation methods. We are currently applying such methods to locating MEQs at Coso.

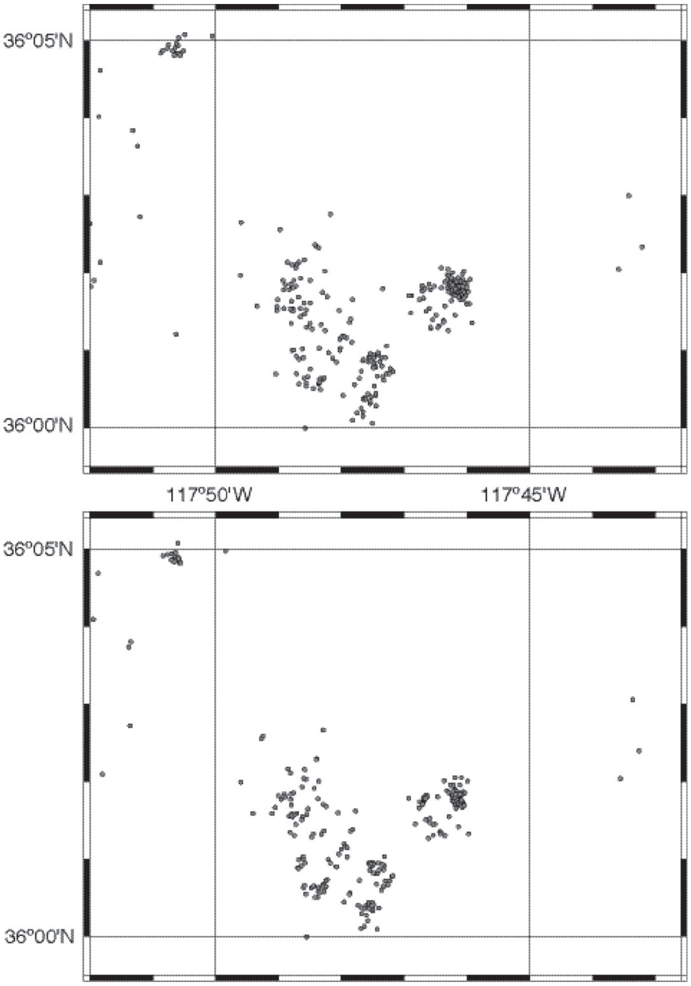

Figure 1. Comparison of conventional (above) and high-resolution (below) earthquake epicenters at Coso for September 2003, based on hand-measured times from the permanent Navy seismometer network. The high-resolution locations are more tightly clustered and better resolve northeast-southwest trends.

Time-dependent tomography — seismic-wave arrival times from MEQs have been used for a number of years to calculate the three-dimensional structure of the volume through which the waves propagate, including several geothermal areas (Arnott and Foulger, 1994; Foulger and others, 2003; Foulger and others, 1995; Foulger and Toomey, 1989; Julian and others, 1996). This technique has recently been extended to four dimensions in order to monitor temporal changes that occur in producing geothermal areas. To date, The Geysers geothermal area has been studied (Gunasekera and others, 2003), and some Indonesian fields where the results are proprietary. This technique is currently being applied to the Coso geothermal field.

Time-dependent tomography requires, for each of two epochs separated by a few years, 100-200 MEQs well distributed throughout the producing field. These should be well recorded on a network of preferably at least 10 seismic stations. If three-component seismometers are deployed then three-dimensional structures can be derived for both compressional and shear wave speeds, V_p and V_s. From these, the V_p/V_s field can be calculated. The changes in seismic wave speed structure that result from production and reinjection activities may be revealed best by any of V_p, V_s or V_p/V_s, depending on whether pore-fluid phase changes, pressure, or mineral dehydration effects are dominant.

Initial results have been obtained for the Coso geothermal field by inverting arrival times measured for sets of about 200 MEQs for each of the years 1996 and 2002 (Foulger and Julian, 2004). The MEQs for 1996 yielded 2243 *P*- and 1439 *S*-phase arrival times. These were inverted to determine simultaneously the earthquake locations and three-dimensional V_p and V_p/V_s structure within a block 10 x 10 km in area and extending from 2 km above sea level to 10 km below sea level. A similar inversion was performed for about 200 earthquakes from 2002, which yielded 2645 *P*- and 1842 *S*-phase arrival times. The V_s structure was calculated from V_p and V_p/V_s, and the results from the two years were differenced to reveal structural changes that occurred in the interim period.

The first-order results are most clearly seen in the V_p/V_s field (Figure 2). The 1996 data show a negative V_p/V_s anomaly in the upper 2 km of the northern part of the producing field (left hand panels, Figure 2a, b). This anomaly became stronger in 2002 (middle panels, Figure 2a, b), so the difference in V_p/V_s between 1996 and 2002 is large (right hand panels, Figure 2a, b). Examination of the separate V_p and V_s fields shows that between 1996 and 2002 both V_p and V_s increased, but increases in V_s dominated, resulting in an increase in the strength of the negative V_p/V_s anomaly. The changes observed are consistent with the replacement of pore water with steam, pressure decrease, or the dehydration of clay minerals. Refinement of these results and inversions of data for intervening years are currently in progress.

Earthquake moment tensors — Recent studies of complete (moment-tensor) source mechanisms show that MEQs at geothermal areas often are accompanied by volume changes, which implies that these events involve processes more complicated than simple shear faulting. These volume changes correlate with commercial exploitation activities, with volume decreases restricted largely to exploited fields, indicating that microearthquake mechanisms are potentially useful for monitoring the effects of exploitation on geothermal systems.

Determining complete moment-tensor earthquake mechanisms is considerably more difficult than determining fault-plane solutions, because of both demands upon seismic-data quality and the effects of complex Earth structure

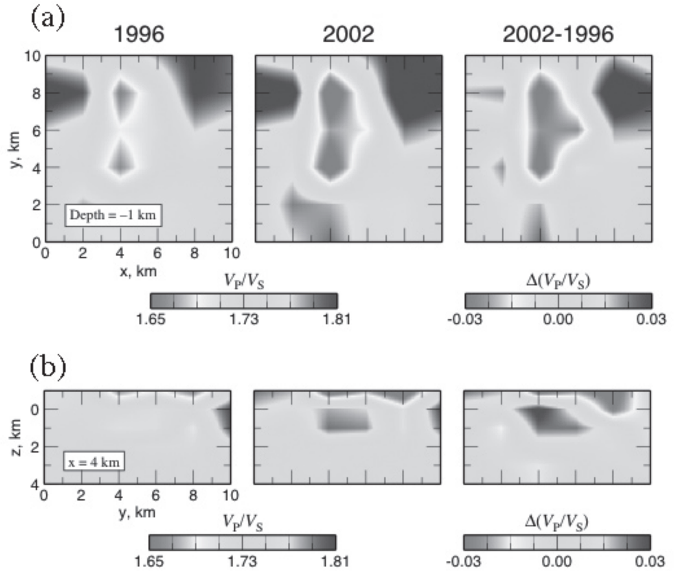

Figure 2. Preliminary tomography results from the Coso geothermal area, showing V_p/V_s structure. (a) Horizontal sections near the surface (1 km above sea level). Left panel: model for 1996; middle panel: model for 2002; right panel: difference between 2002 and 1996. The scale at left applies to the left and middle panels, and the scale at right applies to the right panel. (b) Vertical sections running north-south at x=4 km (refer to (a) for location of section). Left panel: model for 1996; middle panel: model for 2002; right panel: difference between 2002 and 1996. The scale at left applies to the left and middle panels, and the scale at right applies to the right panel. Notice differences in sensitivities of the scales for both (a) and (b).

on seismic waves. An effective technique for reducing bias caused by wave-propagation effects is to invert the ratios of the amplitudes of different seismic phases recorded at a single seismometer (Julian and Foulger, 1996). We are currently applying this method to data from the augmented seismic network at Coso to determine moment tensors for MEQs.

Summary

The utility of microearthquake methods for geothermal prospecting and reservoir monitoring has not been properly evaluated in the past because seismometer networks have seldom provided data of adequate quality. The microearthquake project underway at the Coso geothermal area is, however, underpinned by an excellent seismic network operated by the U.S. Navy that is yielding high-quality microearthquake data. These data, and those forthcoming from the temporary deployment that will monitor the DOE EGS experiment, will provide suitable data for applying modern microearthquake processing techniques such as relative hypocenter location, time-dependent tomography, and earthquake moment-tensor determination. This project is likely to become the definitive example of state-of-the-art MEQ studies at a geothermal area and will facilitate evaluation of the potential of seismic methods for geothermal prospecting and reservoir monitoring.

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