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MONITORING GEOTHERMAL PROCESSES WITH MICROEARTHQUAKE MECHANISMS

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ABSTRACT

The full (moment-tensor) mechanisms of microearthquakes at geothermal areas are valuable for diagnosing processes such as shear faulting and tensile cracking, whether these processes occur naturally, as a by-product of energy extraction, or result from attempts to enhance permeability and geothermal production. Linear-programming provides a robust method for inverting seismic-wave polarity and amplitude-ratio data to determine moment tensors of geothermal microearthquakes in the relevant magnitude range, and this method has by now been successfully applied to many geothermal areas.

We extended the linear programming method to compute confidence regions for moment tensors. This involves adding an inequality constraint to keep the misfit function below a specified limit chosen on the basis of *a priori* estimates of measurement error. The method then moves the solution in six-dimensional moment-tensor space in various specified directions as far as the constraint allows. In this way, within the declared constraints, an envelope enclosing all solutions that fit the data is obtained.

Inverting amplitude ratios for moment tensors using data from several geothermal areas in Iceland, Indonesia, and California shows that mechanisms often, but not always, lie systematically along a trend between the double-couple and the dipole points on the source-type plot (Hudson *et al.*, 1989). Confidence regions computed by our new method are often elongated in the double-couple to dipole direction. This observation suggests that part of the observed systematic trend may be an artifact of measurement error. Further work is required to determine whether all of the trend can be attributed to error, and also to understand why natural earthquakes are distributed in source-type space the way they are.

INTRODUCTION

The moment tensor is a phenomenological description of an earthquake mechanism, which encompasses all the information that can be derived from the radiated seismic waves (Julian *et al.*, 1998). Moment tensors of microearthquakes are increasingly important sources of information about physical processes in geothermal reservoirs. They provide evidence of "non-double-couple" (non-DC) processes, more complicated than simple shear faulting, involving volume changes on time scales of a few milliseconds, with volume increases dominating in natural systems (Miller *et al.*, 1998; Foulger *et al.*, 2004) and both increases and decreases occurring at heavily exploited fields (Ross *et al.*, 1999). Figure 1 shows examples of source types (Hudson *et al.*, 1989) for microearthquakes from three geothermal areas, illustrating some of these observations.

The observations in Figure 1 exhibit systematic features that bear on the physical processes at work, but are not yet thoroughly understood. Most notable is a significant clustering of points near a line connecting the +Dipole and –Dipole loci. This feature is reminiscent of the distribution of source types for combined shear and tensile faulting, which are expected to lie near the line connecting the +Crack and –Crack loci. The observed distributions, however, involve systematically smaller volume changes than are expected for shear-plus-tensile faulting. suggesting that an additional process, such as rapid fluid flow into opening cracks, is at work.

The systematic features in Figure 1 might alternatively be observational artifacts, however. The polarity and amplitude observations used to derive the moment tensors are, like all observations, subject to errors, and these have been mapped in an unknown manner into errors in the derived moment tensors and source types. The resulting errors in the source-type parameters, if they are strongly correlated, might be apparently systematic artifacts on source-type plots. To assess this possibility, the effect of observational errors on the moment-tensor inversion process must be understood. Unfortunately, most moment-tensor analyses of earthquakes to date have lacked any kind of error analysis. We present here the first steps toward providing such analysis for geothermal microearthquakes.

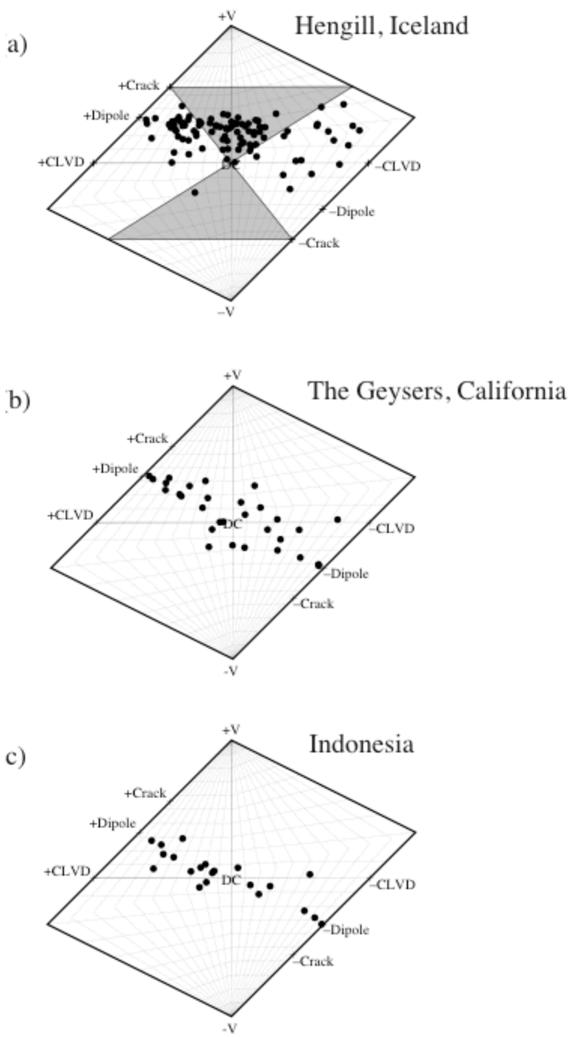

Fig. 1 *Source types for microearthquakes at three geothermal areas, as determined from linear-programming inversion of seismic wave polarities and amplitude ratios. The source type depends only on the ratio of the principal moments, and is independent of source orientation.*

MOMENT-TENSOR INVERSION

Linear Programming Method

The only method currently available for determining seismic moment tensors that applies to microearthquakes (magnitude < 3), and is thus useful for geothermal seismicity, uses linear-programming methods to invert the polarities, amplitudes, and amplitude ratios of compressional and shear elastic waves (Julian, 1986; Julian & Foulger, 1996) recorded by seismometers within a few kilometers of the epicenter. The linear-programming method finds the moment tensor that best fits the observed data in the sense of minimizing the "objective function"

$$F = \sum_{i \in P} w_i |u_i| + \sum_{j \in Q} w_j |u_j - a_j| + \sum_{k \in R} w_k \left| u_k^{(1)} - r_k u_k^{(2)} \right| \qquad (1)$$

The first term is the sum of the theoretical wave amplitudes for those observations whose observed polarities are violated, the second term is the sum of the amplitude residuals, and the third term is the sum of the amplitude-ratio anomalies. In all cases, residuals are measured by their absolute values and individual weights w_i are applied to them.

Interactive graphical software using this method is now available and makes large-scale analysis of geothermal microearthquakes feasible.

Confidence Regions

We have extended the linear-programming method to determine confidence regions for computed moment tensors. The method comes into play after the moment tensor that minimizes the objective function has been found, at which time we add a constraint $F < F_{\max}$ to the problem, where the value of $F_{\max}$ reflects the expected uncertainties in the observations. We then seek to maximize sequentially a suite new objective functions of the form

$$G = \sum_{i=1}^{6} c_i m_i$$

where the m_i are the six independent moment-tensor components and the coefficients c_i are chosen to "push" the source mechanism in some desired direction in moment-tensor space. Possible objective functions might seek to maximize the volume increase or decrease, or to maximize the extension in a chosen direction, for example. Other possibilities involve choosing directions on the basis of the symmetries of regular polytopes (higher-dimensional polyhedra) in six-dimensional space. The suite of derived solutions delineates the region of moment-tensor space for which source mechanisms fit the data adequately.

EXAMPLE

Figure 2 shows three examples of applying the method outlined above to microearthquakes at the Coso geothermal area, California.

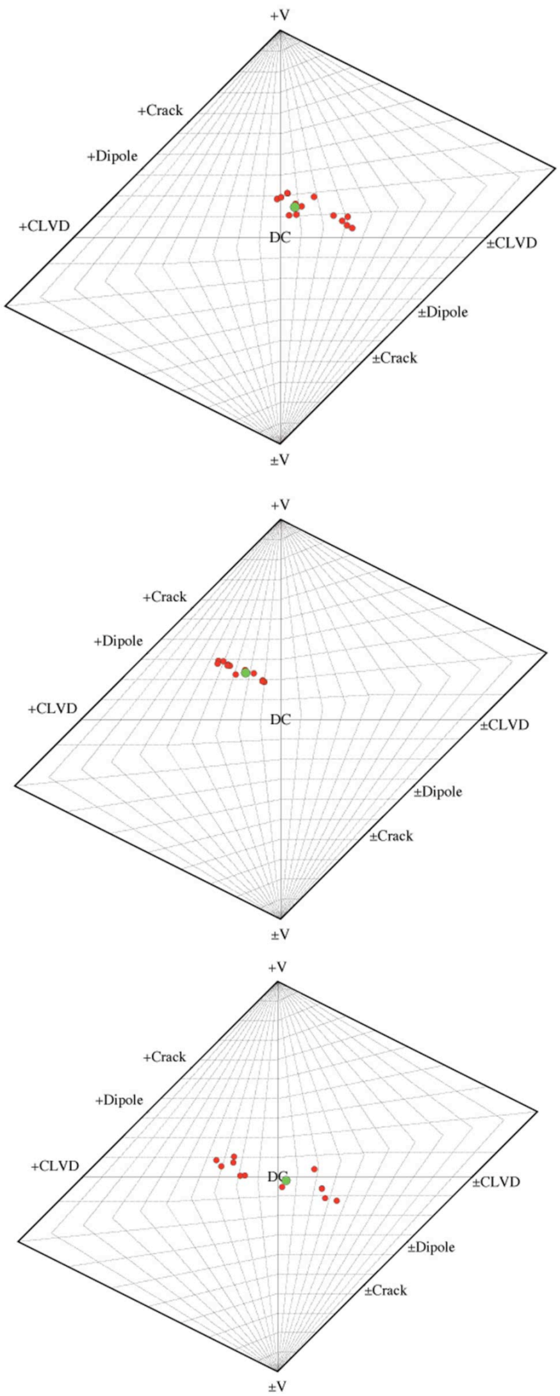

Fig. 2 Examples of confidence regions for the source types of three microearthquakes at the Coso geothermal area, California. Green symbols: best-fit solutions; red symbols: other acceptable solutions that delineate the confidence region.

In all cases, the confidence region delineated by the red symbols slopes downward to the right, and is reminiscent of the trends in the solutions shown in Figure 1. This preliminary example thus suggests that observational error might at least contribute to the observed trends.

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