Applied Microearthquake Techniques for Geothermal Resource Development

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Geothermal areas are often associated with microearthquake activity [Foulger, 1982; Foulger and Long, 1984], and these earthquakes have often been used to learn more about both exploited and unexploited geothermal systems. In recent years, interest in exploiting geothermal energy has increased greatly, accompanied by interest and investment in refining microearthquake analysis techniques, to increase their value in reservoir-development decision making. Of particular interest are techniques relevant to "Engineered Geothermal Systems (EGS)" , which involve increasing the permeability in geothermal reservoirs by hydrofracturing by pumping high-pressure fluid into injection wells in order to create new fault and fracture networks. Exploiting geothermal areas for heat and/or electricity requires extracting hot fluids from buried reservoirs of hot rock. The working fluid used is usually water, although the use of CO_2 is being increasingly discussed.

The microearthquake techniques currently producing the most useful results for geothermal energy production, and which we are currently actively developing, are:

1. *Time-dependent tomography:* Seismically active geothermal areas are well-suited to local-earthquake tomography because earthquakes are often well-distributed throughout the reservoir and production zone. We have studied several geothermal fields, including both unexploited and heavily exploited reservoirs, using *Vp*, *Vs* and *Vp/Vs* tomography. Experience has shown that *Vp/Vs* is particularly useful in imaging exploited fluid zones. Also, progressive depletion of reservoirs can be monitored by tomography repeated every few years. For example, at The Geysers geothermal area, California, a negative *Vp/Vs* anomaly grew remarkably in the period 1991-1998 [Gunasekera *et al.*, 2003]. This anomaly growth correlates with fluid depletion in the reservoir during a period when it was over-exploited.

2. *Accurate microearthquake hypocentral locations:* Accurate microearthquake locations can potentially delineate faults that represent valuable zones of permeability and desirable targets for new production wells. Conventional hypocenter locations are, however, rarely accurate enough to guide the location of new production wells. In recent years, relative relocation techniques have greatly

improved the degree to which microearthquake locations can define separate faults, and we are approaching a situation where new production wells may be sited on the basis of these locations. Excellent results have been obtained simply by using hand-picked *P*- and *S*-wave arrival times [e.g., Foulger and De Luca, 2009], and refining these by waveform cross-correlation is currently also being tested [Julian *et al.*, 2009].

3. *Microearthquake moment tensors:* Geothermal microearthquakes commonly have focal mechanisms that differ radically from the double couples that are consistent with shear slip on planar faults [Julian *et al.*, 1998]. Most commonly, large explosive components are observed, and this has been confirmed by observations in many different geothermal areas. Implosions are also observed, though usually only in exploited reservoirs [Ross *et al.*, 1999]. Such components must represent opening and closing of cavities, often at depths of several kilometres in the Earth's crust. In order to describe such focal mechanisms a full moment tensor description is required, and data in addition to *P*-wave polarities are required to derive them. In order to do this we use a linear-programming technique to invert *P*- and *S*-wave polarities and *P/SV*, *P/SH* and *SV/SH* amplitude ratios [Julian and Foulger, 1996].

Combining the moment tensors of suites of microearthquakes with information on fault orientations from accurate relative relocation techniques, it has been possible at several geothermal fields to obtain detailed information about the locations and modes of failure of geological structures stimulated in hydrofracture experiments [e.g., Julian *et al.*, 2009].

This work is currently developing rapidly, including both methodological development work and applications to case histories. The ultimate goal is to develop an economically viable technology to expand geothermal power production to usefully contribute to expanding renewable energy production and reducing fossil-fuel consumption. We will present several case histories to illustrate the development and current state-of-the-art of these techniques.

References

Foulger, G. R. (1982), Geothermal exploration and reservoir monitoring using earthquakes and the passive seismic method, *Geothermics*, *11*, 259-268.

Foulger, G. R., and L. De Luca (2009), Detailed image of fractures activated by a fluid injection in a producing Indonesian geothermal field, paper presented at Thirty-Fourth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 9-11.

Foulger, G. R., and R. E. Long (1984), Anomalous focal mechanisms; tensile crack formation on an accreting plate boundary, *Nature*, *310*, 43-45.

Gunasekera, R. C., G. R. Foulger, and B. R. Julian (2003), Four dimensional tomography shows progressive pore-fluid depletion at The Geysers geothermal area, California, *J. geophys. Res.*, *108*, DOI: 10.1029/2001JB000638.

Julian, B. R., and G. R. Foulger (1996), Earthquake mechanisms from linear-programming inversion of seismic-wave amplitude ratios, *Bull. seismol. Soc. Am.*, *86*, 972-980.

Julian, B. R., G. R. Foulger, and F. Monastero (2009), Seismic monitoring of EGS stimulation tests at the Coso geothermal field, California, using microearthquake locations and moment tensors, paper presented at Thirty-Fourth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 9-11.

Julian, B. R., A. D. Miller, and G. R. Foulger (1998), Non-double-couple earthquakes I. Theory, *Rev. Geophys.*, *36*, 525-549.

Ross, A., G. R. Foulger, and B. R. Julian (1999), Source processes of industrially-induced earthquakes at The Geysers geothermal area, California, *Geophysics*, *64*, 1877-1889.

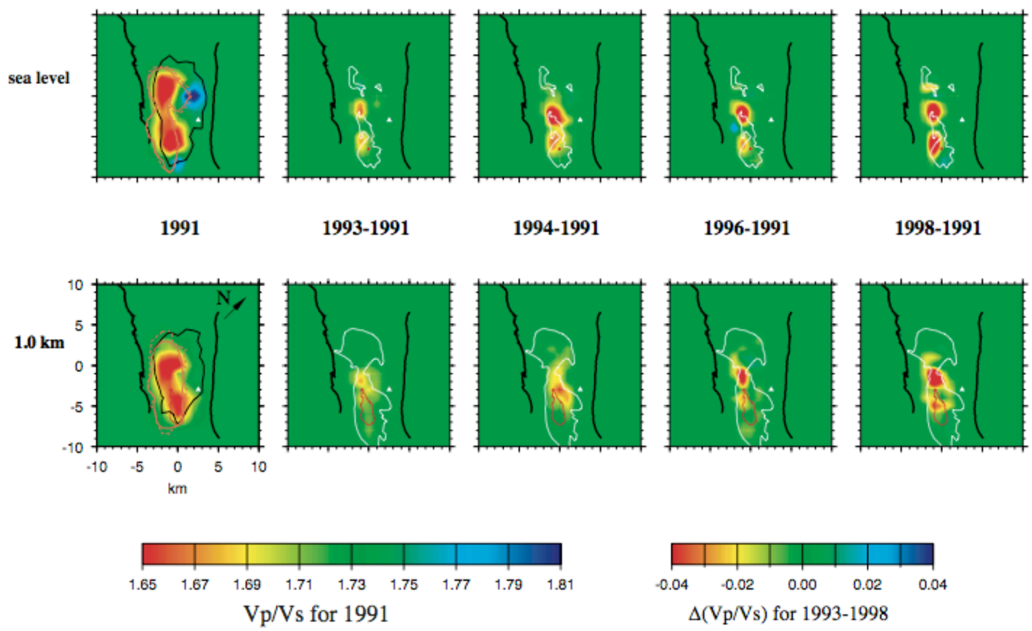

Figure: Anomalies in *Vp/Vs* at sea level (top) and 1.0 km bsl (bottom) for The Geysers geothermal area, California. Left pair of panels, which use the left color scale, show the structure for 1991. The remaining panels, which use the right color scale, show changes from the initial model for subsequent years. The white line encompasses the steam reservoir and the red boundary the felsite batholith that occupies the deeper parts of the reservoir and is thought to be the geothermal heat source [from Gunasekera *et al.*, 2003].