

STUDY OF INDUSTRIALLY INDUCED EARTHQUAKES AT THE COSO GEOTHERMAL AREA, CALIFORNIA

Supervisors

Prof. Gillian R. Foulger & Dr. Bruce R. Julian (U.S. Geological Survey)

Summary

Coso is an exploited geothermal area in the southern Owens Valley, California (Figure 1). This valley is part of the triangular Sierra Nevada - Death Valley transtensional shear zone. Geothermal production activities at Coso induce intense microearthquake activity. This Ph.D. project will involve analysing these microearthquakes to study structure, geothermal processes including fluid-rock interactions, and environmental change. The student will graduate well equipped for a wide variety of careers in science, the environment, management, business and teaching.

Geological and geothermal background

The Coso area is a nascent metamorphic core complex within a releasing bend in a dextral strike-slip system. Northwest-directed transtension is accommodated by normal and strike-slip faulting in the upper 4–6 km of the crust that has been ongoing for 2–3 Myr. Ductile stretching occurs at greater depths, accompanied by shallow igneous intrusions. The thin upper crust overlies a dense mafic intrusion at ~10 km depth that may have formed from cumulates remaining after fractional crystallization of rhyolite, which is represented in local surface domes. Surface volcanism has continued into the Holocene [Monastero *et al.*, 2005]¹.

The area has been exploited for geothermal energy for about a decade, and currently produces ~250 MW of electrical energy². More than 100 boreholes have been drilled and temperatures of up to 342°C have been measured in the centre of the field. Hydrothermal fluids circulate through fracture systems associated with normal and strike-slip faults accommodating a total of ~30 mm of extension annually. Because of its economic importance, the Coso area has been extensively researched, including the acquisition of borehole core, detailed geological mapping and sampling, structural geological modelling, geochemical analyses of rocks and fumarole gases and all foundation geophysical surveying including gravity, magnetics, magnetotellurics and explosion seismology.

With the removal of large volumes of geothermal fluids, the Coso area is undergoing volumetric contraction, which has been measured using GPS and INSAR [Wicks *et al.*, 2001]³. The water table has lowered by several hundreds of metres in recent years. As is common in producing geothermal fields, the area is associated with intense microearthquake activity, much of which is induced by production activities. Experiments to stimulate artificially the formation of new fracture networks and enhance permeability are also underway as part of a major US Department of Energy (DOE) project. These experiments involve pumping water under high pressure into parts of the reservoir with low permeability, and induce hydraulically driven microearthquake sequences that are studied in order to assess the efficacy of hydrofracturing⁴.

¹ <http://bulletin.geoscienceworld.org/cgi/content/abstract/117/11-12/1534>

² http://vulcan.wr.usgs.gov/Volcanoes/California/Coso/description_coso.html

³ <http://quake.wr.usgs.gov/research/deformation/modeling/papers/Coso/CosoJGR2001.html>

⁴ <ftp://dataworks2.library.unr.edu/Geothermal/RoseGBCWksp04.zip>

Microearthquake monitoring

A network of 18 digital, three-component seismic stations, many of them in boreholes, is operated at Coso by the US Navy. It has recorded several thousand locatable earthquakes per year since about 1992. The current database of earthquake locations includes over 80,000 events, for which the original digital seismograms are available. Several basic data-processing techniques have so far been applied to the existing data, involving time-dependent seismic tomography [Figure 2; [Julian *et al.*, 2006](#)]⁵, anisotropy and fault-plane solutions. Initial quality testing of the data for full moment tensors, which give a complete description of the source geometry [Julian and Foulger, 1996], yielded excellent results. These basic results provide a good foundation on which more advanced studies may be based.

Details of the project

The vast seismic database available for the Coso geothermal area is ideal for many detailed analyses that can contribute to understanding the source physics of earthquakes, variations in structure and stress in the area and the nature and evolution of the geothermal field. The project could follow various lines, depending on the student's main interests, and candidate studies could include:

1. Accurate relative relocation of the entire earthquake database and interpretation in terms of detailed structure. Routinely calculated catalogue locations are inaccurate (*e.g.*, Figure 3) and can be spectacularly improved by relative relocations (Figure 4).
2. Derivation of full moment tensors for a suite of key earthquakes, and joint interpretation with accurate locations. This will reveal the geometry, sense of motion, stress and fluid motions in key faults and fault zones [Figure 5; [Julian *et al.*, 2004](#)]⁶,
3. Spatial and temporal variations in fractal dimension of the earthquake distribution throughout the area, which may be related to stress variations. A recent example of a Ph.D. thesis that focused on this aspect is available on the internet⁷.

Other studies that could be conducted include analysis of anisotropy and anelasticity.

A large suite of already-existing advanced location, tomography and moment-tensor seismic processing software will be available to the student. Additional software tools may be implemented or developed as required.

The results will reveal geological structure and spatial and temporal variations in stress, mode and rate of seismic failure, and deformation. The student will interpret them in an interdisciplinary way in conjunction with geological structure, regional deformation from GPS and INSAR, production parameters including fluid volumes removed and reinjected, and data such as gravity, magnetism and the geochemistry of fumarole gases that have bearing on the depth and relationship of the asthenosphere. The objective will be to develop a fully integrated, multidisciplinary result. The project could emphasise any of a choice of themes, *e.g.*, structural geology, applied seismology, geothermal or earthquake physics, depending on the student's preference.

The results might shed light on why such a benign geothermal field exists at all in this rapidly extending part of the Basin and Range province. The Coso geothermal field appears to be

⁵ http://www.dur.ac.uk/g.r.foulger/Offprints/Coso_SGW2006.pdf

⁶ <http://www.dur.ac.uk/g.r.foulger/Offprints/PalmSprings.pdf>

⁷ <http://www.castlebarton.eclipse.co.uk/thesis/index.htm>

essentially unique in this region, but why this should be so is not understood. The discovery of similar fields, perhaps without obvious surface manifestations, would be of extreme importance in view of the current emphasis on developing alternative energy sources.

Additional support

Previous projects co-supervised by U.S. Geological Survey staff have been granted support for the student to spend time working in California each year. It is expected that similar support will be available for the current project.

Your future career

This project will equip the student with a suite of skills embracing earthquake seismology, integrated Earth science research, the scientific method, computing, information technology, presenting scientific results, project management, lecturing, outreach and report writing. Possible future careers include environmental studies, earthquake seismology, geophysics, the geothermal or oil industry, scientific research, geological hazards, computing, business or teaching. A recent graduate who did a similar Ph.D. project was employed for several months by the British Geological Survey to work on the island of Montserrat, contributing to the emergency monitoring of the erupting volcano there.

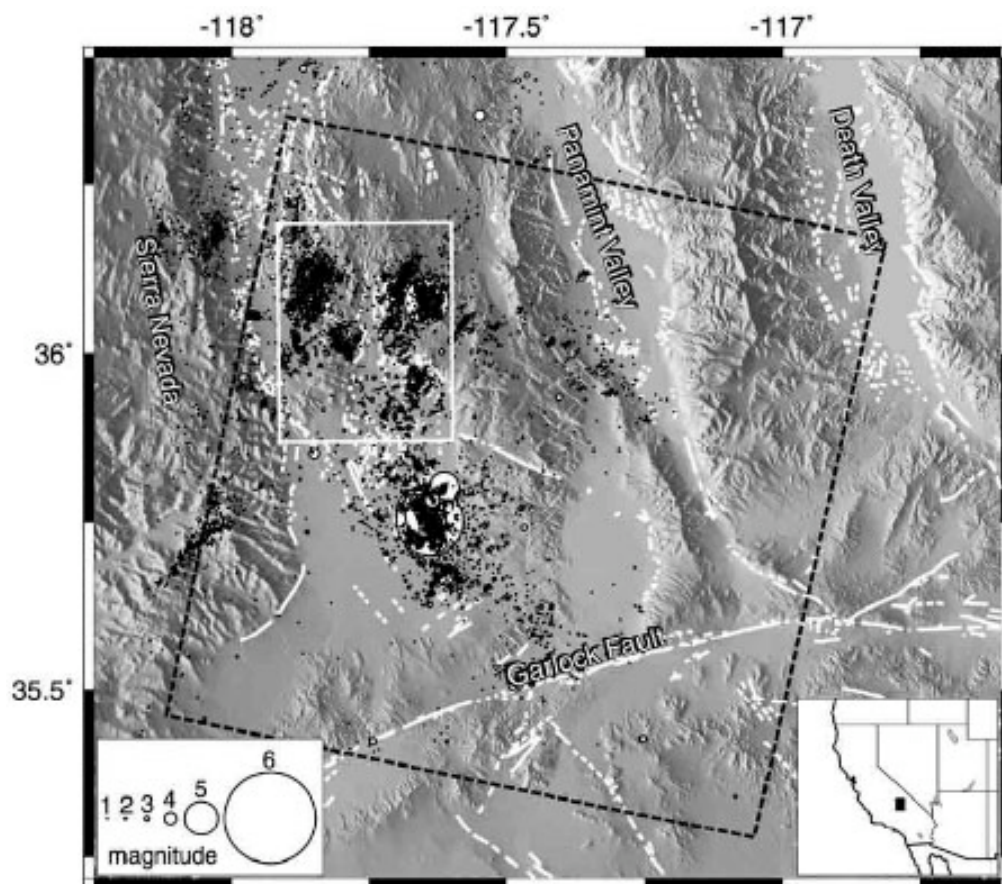


Figure 1. Map of the Coso geothermal area showing regional context (inset). Black dots and circles show the locations of a suite of earthquakes recorded on a regional seismometer network [from [Wicks et al., 2001](#)]³.

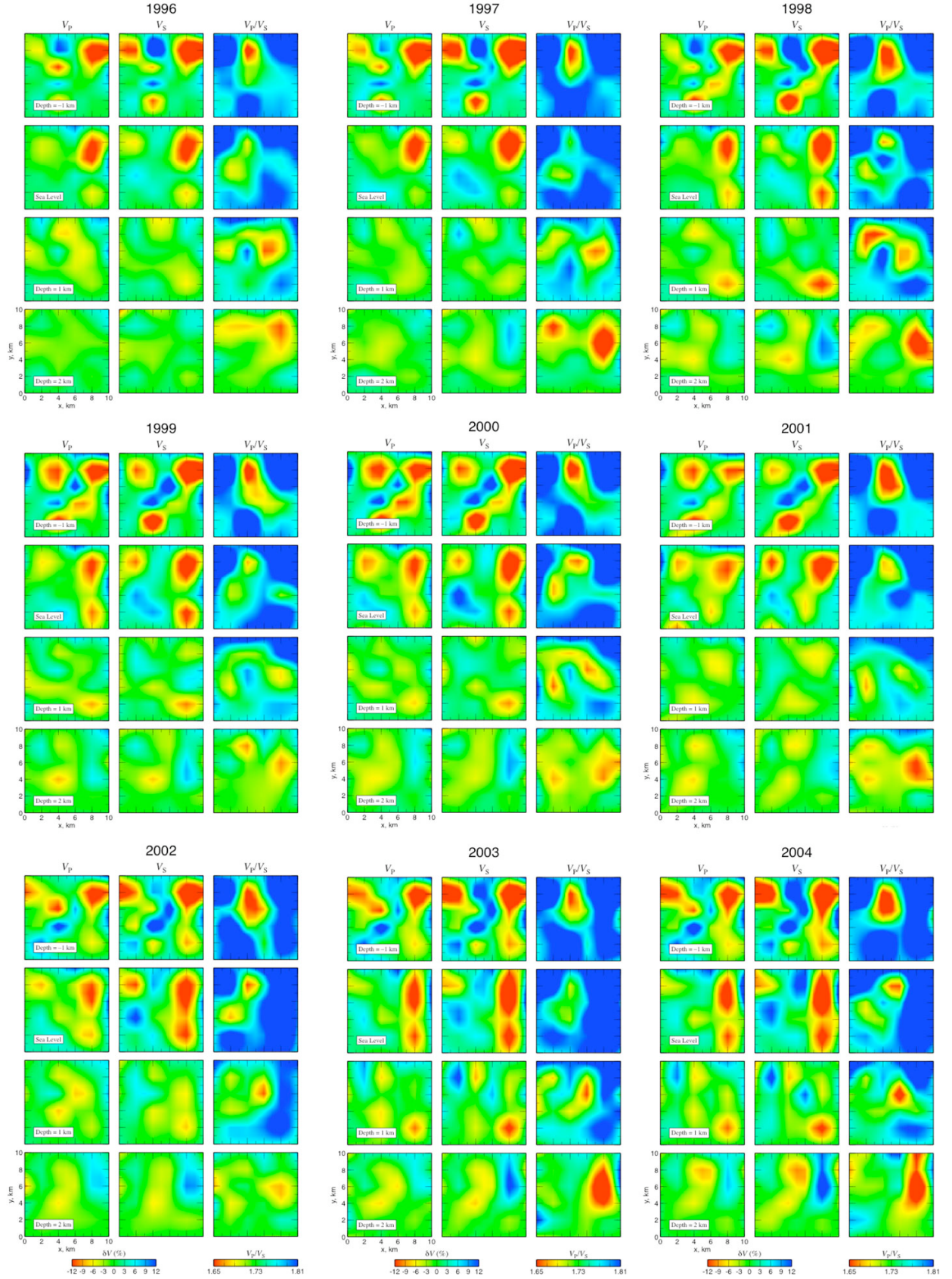


Figure 2. Maps of the Coso geothermal area showing the compressional and shear wave speeds V_p , V_s , and the V_p/V_s ratio at different depths for the years 1996-2004 [from Julian *et al.*, 2006]⁵.

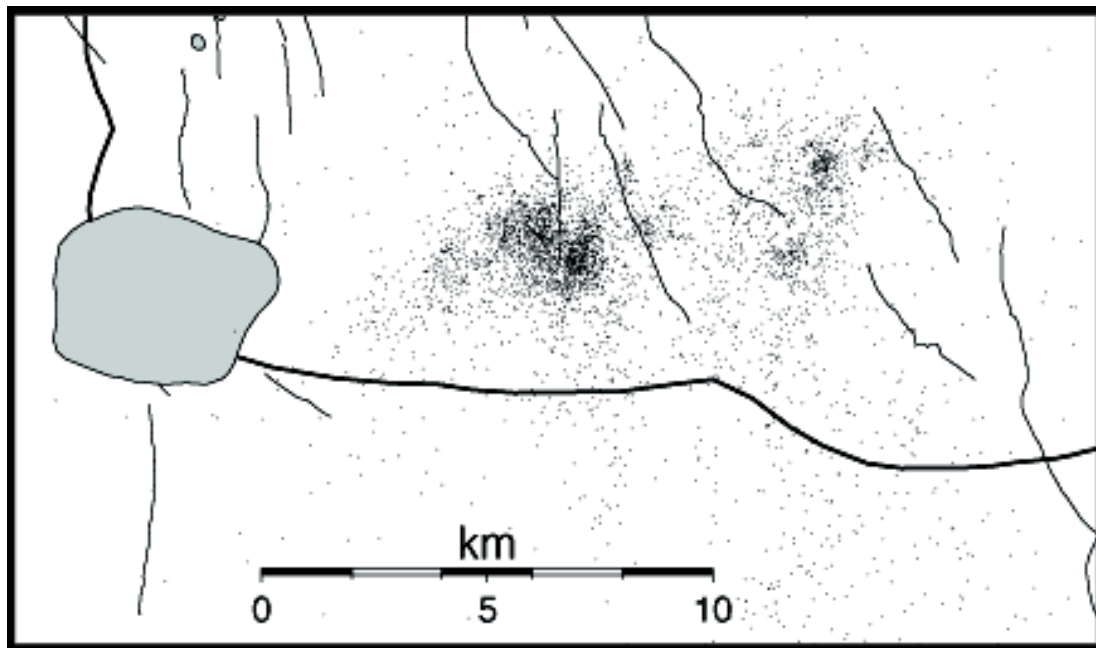


Figure 3. Map of part of Long Valley Caldera, California, showing catalogue earthquake locations.

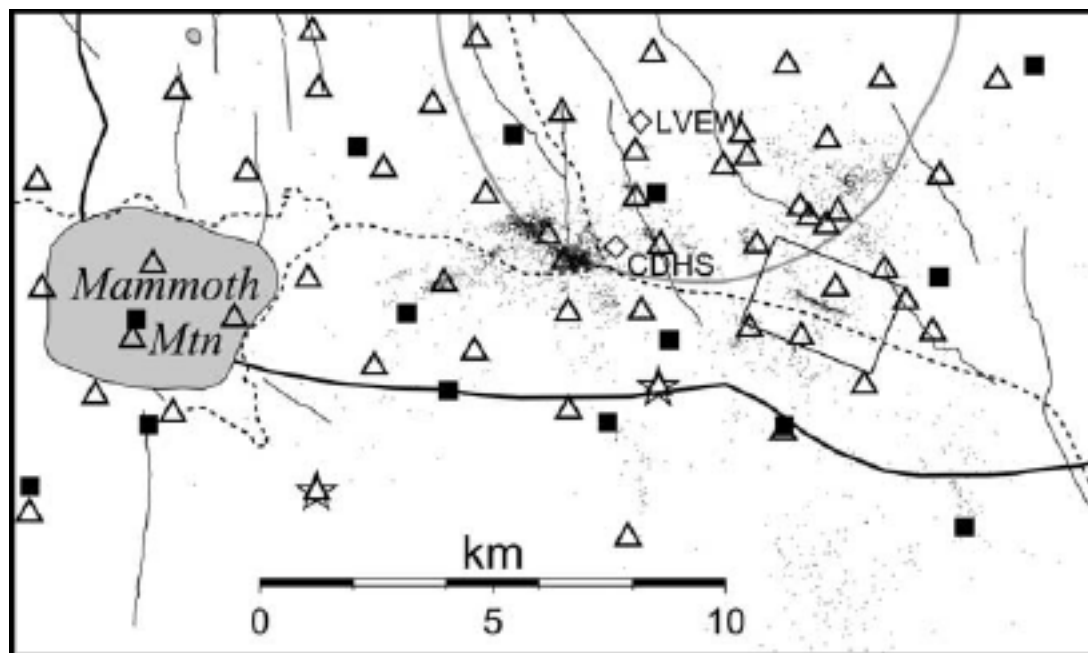


Figure 4. Map of the same area as shown in Figure 1, with relatively relocated earthquake locations plotted. Note the much improved quality of locations, particularly in the area shown in the box, compared with Figure 2 [from Foulger *et al.*, 2004]⁸.

⁸ <http://www.dur.ac.uk/g.r.foulger/Offprints/MammothFM.pdf>

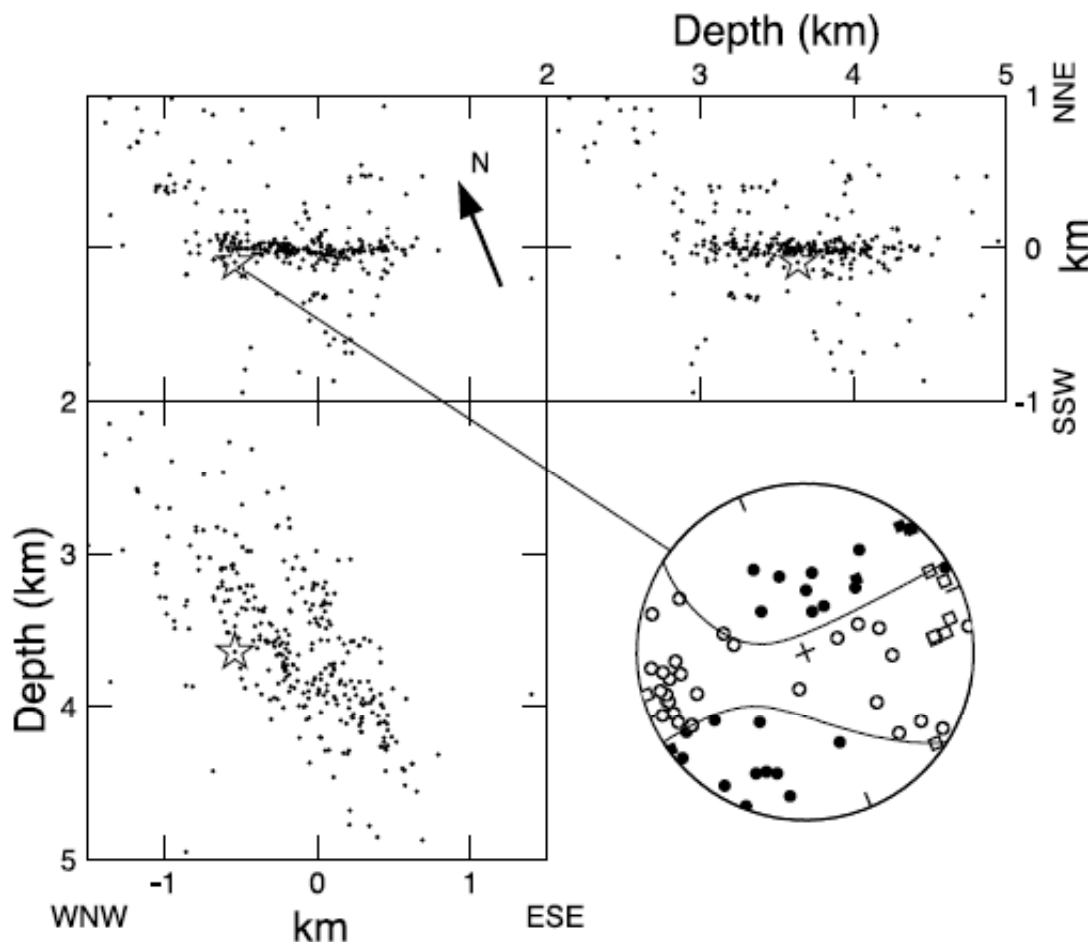


Figure 5. Non-shear earthquake focal mechanism, compared with accurate earthquake relocations for the sequence shown in the box in Figure 3. The mechanism for this earthquake is incompatible with shear faulting on this plane, but compatible with compensated tensile failure [from Foulger *et al.*, 2004]⁸.

- Foulger, G. R., B. R. Julian, D. P. Hill, A. M. Pitt, P. Malin, and E. Shalev (2004), Non-double-couple microearthquakes at Long Valley caldera, California, provide evidence for hydraulic fracturing, *J. Volc. Geotherm. Res.*, 132, 45-71.
- 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 K. Richards-Dinger (2004), The Coso Geothermal Area: A Laboratory for Advanced MEQ Studies for Geothermal Monitoring, paper presented at Geothermal Resources Council Annual Meeting, Geothermal Resources Council, Palm Springs, August 2004.
- Julian, B. R., G. R. Foulger, K. Richards-Dinger, and F. Monastero (2006), Time-dependent seismic tomography of the Coso geothermal area, 1996-2004, paper presented at Thirty-First Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 30-February 1, 2006.
- Monastero, F. C., A. M. Katzenstein, J. S. Miller, J. R. Unruh, M. C. Adams, and K. Richards-Dinger (2005), The Coso geothermal field: A nascent metamorphic core complex, *Bull. Geol. Soc. Am.*, 117, 1534-1553.
- Wicks, C., W. Thatcher, F. Monastero, and M. Hasting (2001), Steady-State Deformation of the Coso Range, East-Central California, Inferred from Satellite Radar Interferometry, *J. geophys. Res.*, 106, 13769-13780.