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Relation Between Local Strain Perturbations and Relief on the Brittle-Ductile Transistion Zone, Coso Range, Eastern California

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ABSTRACT

The brittle-ductile transition occurs at a depth of about 4 km beneath the Coso geothermal field, eastern California, and exhibits approximately 5 km of positive relief relative to surrounding areas. The shallowing of the brittle-ductile transition at Coso occurs in an area of localized extension and volcanism associated with a releasing stepover between major strike-slip faults. We investigated patterns of brittle deformation at Coso by inverting groups of microearthquake focal mechanisms for components of a best-fit incremental strain tensor. The inversion results reveal systematic rotations of the maximum extension (d_1) and maximum shortening (d_3) axes across the central Coso Range. In Rose Valley to the west of the geothermal field, both d_1 and d_3 are subhorizontal, and their orientations are consistent with regional NW-directed dextral shear and right-lateral strike-slip faulting. These principal strains rotate from the horizontal plane in Rose Valley to the vertical plane along the west flank of the Coso Range, where d_1 and d_3 show comparable plunges in opposite directions. Here the deformation is associated with east-down vertical shear on blind, seismogenic faults. Moving into the geothermal field, the principal strains rotate to a new orientation where d_1 is horizontal and d_3 is vertical, indicating crustal thinning, which is accommodated by normal faulting. East of the geothermal field, the principal strains rotate back to their regional horizontal trends. We suggest that the observed variation in strain, and presumably stress, may be controlled by the local rise in the brittle-ductile transition beneath the geothermal field. We assume that the brittle-ductile transition is a surface or zone that cannot support high shear stress, and thus the principal stresses and strains must intersect the transition zone at either high or low angles. The model predicts that the principal stresses and strains systematically rotate from their regional trends to maintain low shear stress on the ramp in the brittle-ductile transition as it shallows beneath Coso, consistent with our observations. If this is correct, then releasing stepovers like Coso that become loci of volcanism and geothermal activity

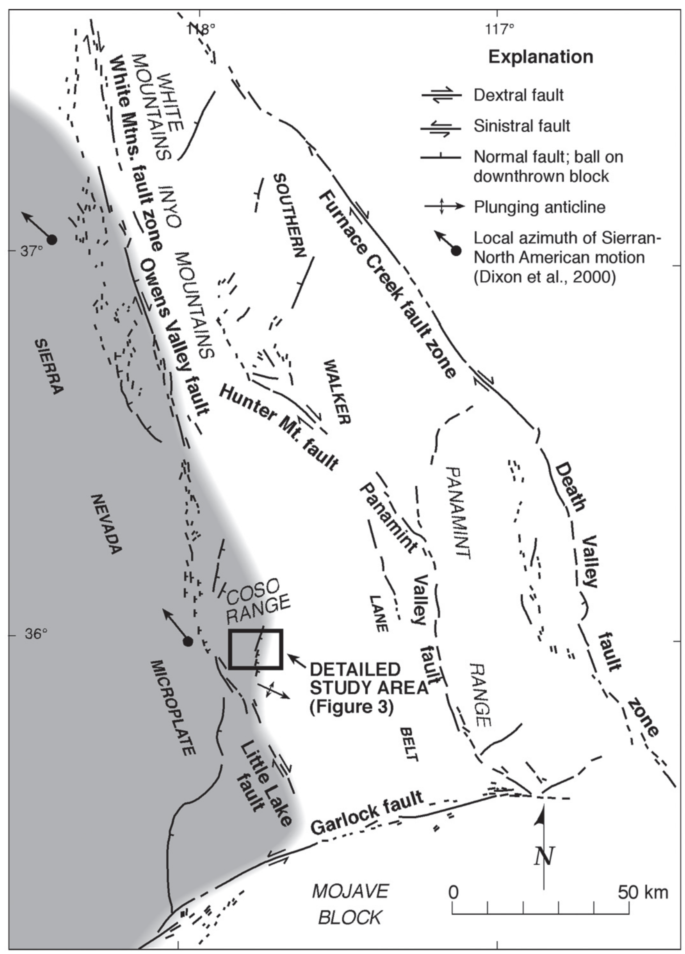

Figure 1. Active strike-slip and normal faults of the southern Walker Lane belt (Jennings, 1994), and location of the study area in the central Coso Range. Shaded area represents the Sierra Nevada microplate. Arrows indicate motion of the Sierra Nevada with respect to stable North America.

may effectively dominate the geometry of the local stress and deformation field.

Introduction

This paper presents an analysis of microearthquakes in the central Coso Range, a region of active strike-slip and normal faulting in eastern California (Figure 1). We use the dense distribution of seismicity in this region to map three-dimensional patterns of active strain within and adjacent to the Coso geothermal field, a world-class hydrothermal system that has been producing an average of 270 MW of electricity for the past fourteen years. Crustal thinning in the Coso Range been accompanied by intrusion of hot, mafic material into the lower crust, thus providing the heat for the geothermal system. In this study, we document systematic variations in crustal strain that are spatially associated with shallowing of the brittle-ductile transition zone beneath the producing area.

Transtensional Setting of the Central Coso Range

The Coso geothermal field is located within the transtensional Walker Lane belt, a 100-km-wide zone of distributed right-lateral shear in eastern California and western Nevada that borders the Sierra Nevada range. Geodetic observations and seismotectonic analyses indicate that active deformation in the Walker Lane belt primarily accommodates northwest translation of the Sierra Nevada as a block or microplate with respect to stable North America (Argus and Gordon, 1991 and 2001; Dixon et al., 1995 and 2000; King et al., 1999; Unruh et al., 2003) (Figure 1).

Active crustal extension in the Walker Lane belt, including the Coso Range, generally is associated with releasing transfers of slip among major right-lateral strike-slip faults (Unruh et al., 2003). Coso Wash, a north-south-trending asymmetric graben in the east-central part of the Coso range, is a pull-apart basin in the right (releasing) stepover between the Airport Lake fault zone to the south, and the Owens Valley fault to the north. Coso Wash is bounded on the west by the Coso Wash fault (Figure 1), which exhibits geomorphic evidence for Holocene normal displacement (Roquemore, 1981). Coso Wash is bordered on the east by a distinctive step-faulted terrain that deforms Pliocene basalt flows of Wild Horse Mesa (Figure 2). The step-faulted terrain terminates eastward against the NW-striking, left-stepping Wild Horse Mesa fault zone (WHMFZ on Figure 2; Lewis and Pluhar, 2003).

Earthquake Data and Analysis

Earthquake data used in this study were recorded by the US Navy's seismographic network in the Coso Range, a sixteen-station network of high-frequency (4 hz) downhole sensors. The network routinely records well-located events as small as M –2.0. The vast majority of microseismicity in and around the geothermal field is confined to the upper 4 to 5 km of the crust. In Rose Valley to the west of the geothermal field, seismicity extends to about 8-10 km, reaching depths of about 12 km adjacent to the Sierra Nevada (Unruh and Hauksson, 2003); focal mechanisms indicate that the seismicity there is associated with right-lateral strike-slip faulting. Beneath Wild Horse Mesa to the east, seismicity extends to depths of 8-9 km, and cross sections of hypocenters reveal the presence of a seismogenic, but blind, NW-striking dextral fault (Unruh et al., 2002). We interpret this blind strike-slip fault to be part of the eastern boundary of the releasing stepover between the Airport Lake and Owens Valley faults.

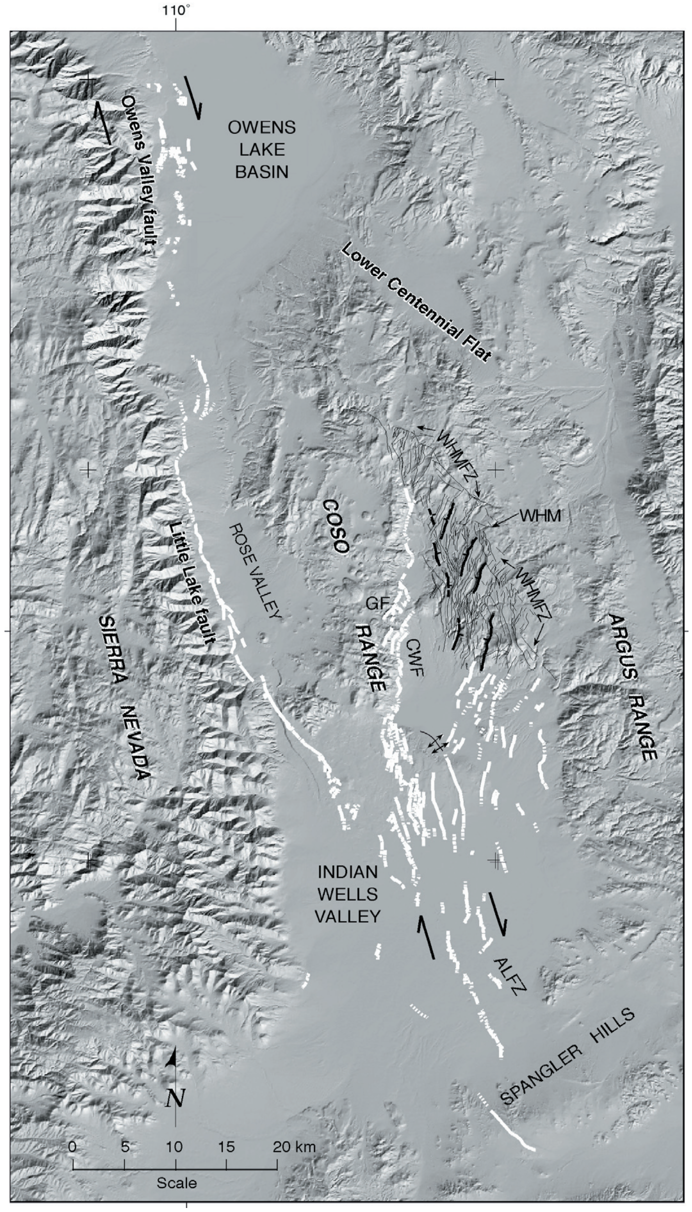

Figure 2. Major active faults (in white) that form the eastern tectonic boundary of the Sierra Nevada microplate in the southern Walker Lane belt. Faults highlighted in black in Wild Horse Mesa (WHM) are late Cenozoic faults with especially prominent scarps in Pliocene volcanic flows. ALFZ = Airport Lake fault zone; CWF = Coso Wash fault; WHMFZ = Wild Horse Mesa fault zone.

To evaluate seismogenic strain in the central Coso Range, we inverted seismic P and T axes from groups of focal mechanisms for the components of a reduced incremental deformation tensor using to the approach of Twiss et al.

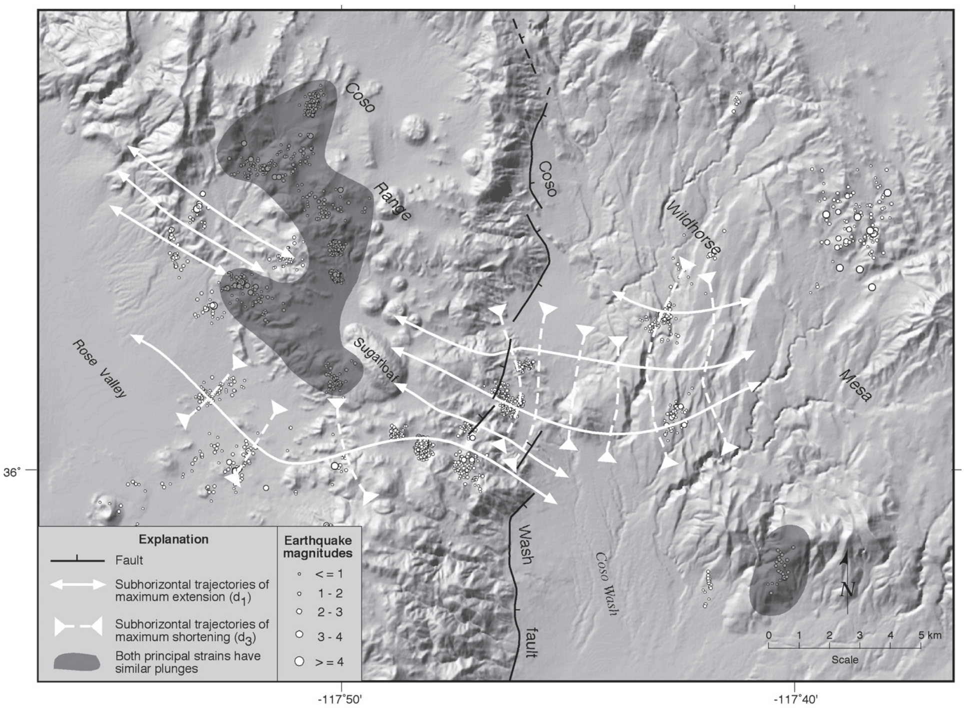

Figure 3. Map of the seismogenic deformation field in and around the Coso geothermal field, which is located between Sugarloaf Mountain and Coso Wash. Epicenters of earthquakes used in the analysis are shown by small circles. See text for further explanation.

(1993) and Twiss and Unruh (1998). The best-fit model from the inversion provides values for the five model parameters: three parameters define the orientations of the principal incremental strains ($d_1 > d_2 > d_3$ lengthening reckoned positive); a scalar parameter D, defined by a ratio of the differences in the principal incremental strains, that characterizes the shape of the incremental strain ellipsoid; and a scalar parameter W, the relative vorticity, that characterizes the incremental rotation of rigid, fault-bounded blocks relative to the incremental rotation of the large-scale continuum, about an axis parallel to the intermediate principal strain d_2 (Twiss et al., 1993). For this paper, we focus exclusively on the orientations and relative magnitudes of the principal incremental strains, since the relative vorticity is a kinematic variable of local significance only.

The inversion results are synthesized in a map of the seismogenic deformation field within and adjacent to the geothermal production area (Figure 3). The horizontal components of the deformation are depicted by trajectories drawn parallel to the trends of d_1 (maximum extension axes; solid lines on Figure 3) and d_3 (maximum shortening axes; dashed lines on Figure 3). Where d_1 and d_3 are both subhorizontal and form a grid-like pattern on the map, the style of deformation is characterized by horizontal plane strain and crustal shearing. If one or both of d_1 or d_3 are steeply plunging to subvertical, their respective trajectories are not plotted on the map. In these cases, the seismogenic deformation is characterized by net crustal thickening (d_1 vertical) or net thinning (d_3 vertical).

Seismogenic Strain In and Around the Coso Field

Seismogenic deformation in the Coso production area is characterized by horizontal extension (horizontal d_1) and crustal thinning (vertical d_3; Figure 3). The NW-SE trend of d_1 in the geothermal field is parallel to regional trends, indicating that earthquakes induced by production and injection activites are releasing tectonic strains associated with the regional deformation, and not randomly oriented strains of local origin.

The inversion results reveal two areas of unusual strain geometry adjacent to the geothermal field (i.e., shaded areas in Figure 3), where the d_1 and d_3 strains plunge about 45° in opposite directions. These strain orientations are shown in a general NW-SE cross-section through the study area (Figure 4). Hypocenters of earthquakes at about 2 km depth directly west of Sugarloaf Mountain define a vertical fault, and inversion of focal mechanisms from these events indicate that d_1 plunges SE and d_3 plunges NW, consistent with east-side-down shear on the fault (Figure 4). Inversion of focal mechanisms from a small cluster of earthquakes at the south end of Wildhorse Mesa east of the geothermal field similarly indicates that the extensional and shortening strains are plunging in

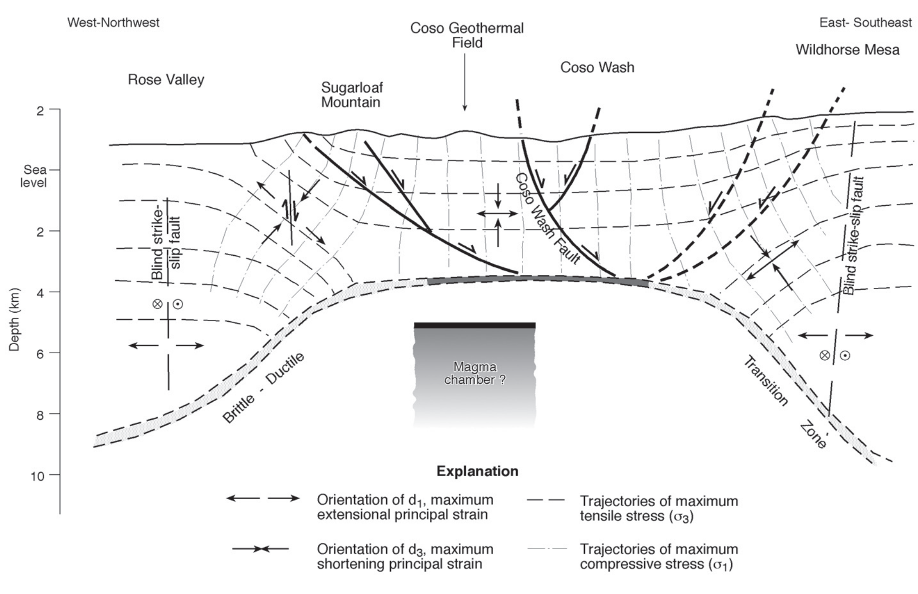

Figure 4. Model for perturbation of regional stresses and strains by shallowing of the brittle-ductile transition zone above a mid-crustal magma chamber beneath the Coso geothermal field.

opposite direction, but their orientations are reversed relative to the area west of Sugarloaf Mountain (Figure 4).

The unusual orientations of the principal strains, with d_1 and d_3 both plunging about 45° in opposite directions, are part of a systematic variation in the strain geometry from west to east across the central Coso Range (Figure 4). In Rose Valley to the west of the geothermal field, both d_1 and d_3 are subhorizontal and associated with NW-directed right-lateral shear and strike-slip faulting (Figure 3; also, Unruh et al., 2002). The principal d_1 and d_3 strains rotate from the horizontal plane in Rose Valley to the vertical plane along the west flank of the Coso Range, where they plunge in opposite directions. Moving east into the geothermal field, the principal strains rotate to a new orientation where d_1 is horizontal and d_3 is vertical, and the deformation is characterized by crustal thinning accommodated by normal faulting . Beneath southern Wild Horse Mesa east of the geothermal field, d_1 rotates into the vertical plane and plunges 45° in an opposite direction to d_3, which also plunges about 45°. Farther east, Unruh et al. (2002) found that both d_1 and d_3 resume their regional horizontal orientations, consistent with regional NW dextral shear in the southern Walker Lane belt.

Interpretation

We infer that the base of seismicity in this region is parallel to, if not coincident with, the transition from brittle to ductile deformation. If this is correct, then the depth distribution of seismicity suggests that the brittle-ductile transition is as shallow as about 4 km beneath the Coso geothermal field, and as deep as 8 to 10 km in areas to the west and east. The shallowing of the brittle-ductile transition occurs above what workers have interpreted to be a mid-crustal magma chamber (e.g., Reasenberg et al., 1980). Based on analysis of teleseisms, Wilson et al. (2003) observed a low velocity zone at a depth of about 6 km beneath the producing area that they interpreted to be the top of the magma chamber.

The possibility that the brittle-ductile transition may be as shallow as 4 km beneath the geothermal field is supported by temperature data from selected wells. Fournier (1999) discussed the nature of the brittle-ductile transition in hydrothermal settings and noted that for silicic systems, it occurs at approximately the 350°C isotherm for a range of tectonic strain rates that is appropriate for the Coso Range and the southern Walker Lane belt. Table 1 is a compilation of temperatures, temperature gradients, and depths from wells within the Coso field and, for comparison, two wells in other locations that have penetrated the brittle-ductile transition. Based on the thermal gradients shown in Table 1, the 350°C isotherm probably occurs at depths of about 4 km in the Coso system.

Our inversion results show that the trajectories of the principal incremental strains are vertical and horizontal at the earth's surface, and that d_1 and d_3 are essentially equally inclined in a vertical plane at depth along the blind faults east and west of the Coso field (Figure 4). We propose that the variations in strain orientation across the Coso Range are controlled by relief on the brittle-ductile transition. Our model is based on two assumptions. First, we assume that, to a first approximation, the crustal rocks are mechanically isotropic, which means the orientations of the principal stresses are parallel to those of the principal incremental strains (Twiss and Unruh 1998). Second, we assume that the brittle-ductile transition does not support large shear stresses. This assumption seems reasonable, based on the interpretation of the brittle-ductile transition as a zone of high pore fluid pressure (Fournier, 1999), which would reduce resistance to frictional sliding to very low shear stresses. Onset of ductile deformation mechanisms within this zone would also act to relax any build-up of shear stresses on this boundary. This second assumption, therefore, would require the trajectories of the principal stresses to intersect the brittle-ductile transition at high or low angles, a geometry that minimizes the resolved shear stress parallel to the transition zone. With these assumptions, the observed rotation of the incremental strain trajectories from their regional horizontal trends at shallow depths to moderate plunges along the margins of the field (Figure 4) can be explained in terms of the requirement that shear stresses remain very low parallel to the brittle-ductile transition. Where the brittle-ductile transition ramps up to shallower depths beneath the Coso geothermal field, the orientations of the principal stresses must rotate in order to maintain low resolved shear stress on the inclined portion of the transition zone.

Interestingly, d_3 (maximum shortening) is vertical in the production area, rather than horizontal in Rose Valley to the west and Coso Wash (and regionally in the southern Walker Lane belt). This implies that crust in the producing area is being lengthened in a NW-SE direction and thinned, while crust bordering the field is being sheared. We speculate that the elevation of the geotherms in the vicinity of the geothermal field has effectively lowered the mean strength of the crust by markedly elevating the brittle-ductile transition. This weakening has concentrated the divergent component of strain, producing "necking" of the ductile crust above the intrusion and associated thinning of the brittle carapace above the brittle-ductile transition.

Table 1. P-T Parameters for Selected Coso and Other Wells

Well	TD (m)	P (max) bars	T (max) °C	T (grad)* °C/km	P (hydro) bars	P (litho) bars	Depth (m) @400°C
A.	2,713	172	305	106	285	650	3,744
B.	2,594	217	334	120	273	622	3,333
C.	3,968	242	336	85	417	951	4,706
D.	2,967	192	341	109	312	711	3,670
E.	3,048	172	350	115	321	731	3,478
Kakkonda WD-1A	3,729	N.R.	515	133	392	894	3,400
San Pompeo 2	2,930	240	>400	125	308	703	<2,930

*Average ambient air temperature = 17.8°C

Conclusions

Our kinematic inversions of microseismicity reveal systematic variations in strain geometry across the Coso geothermal field. We propose a simple model that relates local rotation of the principal strains to positive relief on the brittle-ductile transition above a midcrustal magma chamber and beneath the producing zone. If correct, this interpretation suggests that releasing stepovers like Coso, which are loci of volcanism and geothermal activity, may locally perturb the regional transtensional strain field and concentrate crustal thinning.

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References

Argus, D.F., and Gordon, R.G., 1991, Current Sierra Nevada-North America motion from Very Long baseline interferometry: implications for the kinematics of the western United States: Geology, v. 19, p. 1085-1088.

Argus, D.F., and Gordon, R.G., 2001, Present tectonic motion across the Coast Ranges and San Andreas fault system in central California: Geological Society of America Bulletin, v. 113, p. 1580-1592.

Dixon, T.H., Robaudo, J.L., and Reheis, M.C., 1995, Constraints on present-day Basin and Range deformation from space geodesy: Tectonics, v. 14, p. 755-772.

Dixon, T.H., Miller, M., Farina, F., Wang, H., Johnson, D., 2000, Present-day motion of the Sierra Nevada block and some tectonic implications for the Basin and Range province, North American Cordillera: Tectonics, v. 19, p. 1-24.

Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

King, R.W., Hager, B.H., McCluskey, S.C., and Meade, B.J., 1999, Reduction and utilization of GPS data from the Navy geothermal crustal motion network: Final Technical Report prepared for the Geothermal Program Office, Naval Air Warfare Center, China Lake, CA, Contract No. N68936-95-C-0371, 30 p.

Lewis, J.C., and Pluhar, C.J., 2003, Pliocene to Recent kinematics of the Wild Horse Mesa and Coso Wash: an integrated study using micropolat theory and paleomagnetic determinations to examine spatial and temporal variations in strain: Final Technical Report prepared for the Geothermal Program Office, Naval Air Warfare Center, China Lake, CA, Contract No. N68936-01-C-0094, 98 p.

Reasenberg, P., Ellsworth, W., and Walter, A., 1980, Teleseismic evidence for a low-velocity body under the Coso geothermal resource area: Journal of Geophysical Research, v. 85, p. 2471-2483.

Twiss, R.J., Souter, B.J., and Unruh, J.R., 1993, The effect of block rotations on the global seismic moment tensor and patterns of seismic P and T axes: Journal of Geophysical Research, v. 98, 645-674, 1993.

Twiss, R.J., and J.R. Unruh, 1998, Analysis of fault-slip inversions: do they constrain stress or strain rate?: Journal of Geophysical Research, v. 103, p. 12,205-12,222.

Unruh, J.R., Hauksson, E., Monastero F.C., Twiss, R.J., and Lewis, J.C., 2002, Seismotectonics of the Coso Range-Indian Wells Valley region, California: Transtensional deformation along the southeastern margin of the Sierran microplate, in Glazner, A.F., Walker J.D., and Bartley, J.M., eds., Geologic Evolution of the Mojave Desert and Southwestern Basin and Range: Boulder, Colorado, Geological Society of America Memoir 195, p. 277-294.

Unruh, J.R., and Hauksson, E., 2003, Characterization of upper crustal velocity structure and seismogenic deformation, southern Walker Lane belt and eastern Sierra Nevada, California: Final Technical Report prepared for the Geothermal Program Office, Naval Air Warfare Center, China Lake, CA, Contract No. N68936-02-C-0207, 47 p.

Unruh, J., Humphrey, J., and Barron, A., 2003, Transtensional model for the Sierra Nevada frontal fault system, eastern California: Geology, v. 31, p. 327-330.

Walter, A. W., and C. S. Weaver, 1980, Seismicity of the Coso Range, California: Journal of Geophysical Research, v. 85, p. 2441-2458.

Wilson, C. K., Jones, C. H. , and Gilbert, H. J., 2003, Single-chamber silicic magma system inferred from shear wave discontinuities of the crust and uppermost mantle, Coso geothermal area, California: Journal of Geophysical Research, v. 108, *doi:10.1029/2003.*