Transtensional model for the Sierra Nevada frontal fault system, eastern California

Jeffrey Unruh William Lettis & Associates, Inc., 1777 Botelho Drive, Suite 262, Walnut Creek, California 94596, USA
James Humphrey Lahontan GeoScience, Inc., 1105 Terminal Way, Suite 202, Reno, Nevada 89502, USA
Andrew Barron William Lettis & Associates, Inc., 1777 Botelho Drive, Suite 262, Walnut Creek, California 94596, USA

ABSTRACT

Active strike-slip and normal faults along the eastern margin of the Sierra Nevada primarily accommodate northwestward translation of the Sierra Nevada–Central Valley (i.e., Sierran) microplate with respect to stable North America. Strike-slip faults bordering the eastern Sierran microplate are subparallel to small circles about the Sierra Nevada–North American Euler pole. Normal faults of the Sierra Nevada frontal fault system strike ~45° clockwise of the small circle trajectories and exhibit well-defined, left-stepping en echelon patterns, consistent with formation in dextral transcurrent regime. Major graben bordering the northeastern Sierran microplate are located in regions where the locus of range-front deformation steps abruptly eastward in a releasing geometry relative to Sierra Nevada–North American motion. Crustal shortening occurs at the northern end of the Sierran microplate, where a component of northwest dextral shear steps westward in a left-restraining geometry across the Sierran crest to the Sacramento Valley. Kinematic inversions of earthquake focal mechanisms from the Walker Lane belt bordering the eastern Sierra Nevada indicate that seismogenic deformation primarily is characterized by horizontal shearing and oblique crustal thinning. Directions of macroscopic dextral shear inferred from the inversions are subparallel to the trajectories of small circles about the Sierra Nevada–North American Euler pole. Normal faulting along most of the eastern Sierran range front thus appears to primarily accommodate microplate translation rather than Sierran uplift or regional Basin and Range extension.

Keywords: Sierra Nevada, Walker Lane, neotectonics, seismotectonics, geodesy, structure.

INTRODUCTION

The Sierra Nevada and large areas of central California move as an independent microplate within the 1500-km-wide boundary between the Pacific plate and stable North America (Argus and Gordon, 1991; Wernicke and Snow, 1998). Plate-boundary motion steps eastward from the San Andreas fault system in southern California to the eastern California shear zone, a 100-km-wide belt of seismicity and active strike-slip faulting that can be traced northward from the Salton trough across the central Mojave block (Dokka and Travis, 1990; Savage et al., 1990; Unruh et al., 1996a) (Fig. 1). The eastern California shear zone probably transfers ~20%–25% of Pacific–North American plate motion to the interior of the Cordillera east of the Sierra Nevada (Sauber et al., 1994; Bennett et al., 1999; Dixon et al., 2000). Geodetically determined motion of the Sierran microplate relative to North America can be described as a counterclockwise rotation about an Euler pole located west of the coast of southern California (Argus and Gordon, 1991; Dixon et al., 2000). From south to north along the microplate, the azimuth of Sierra Nevada–North American motion turns progressively westward, varying from ~N43°W at the southeast end of the range to ~N56°W at the northern end of the range. In this paper we assess the role of active strike-slip and normal faulting along the eastern margin of the Sierran microplate in the context of rigid block translation parallel to Sierra Nevada–North American motion (Fig. 1).

Figure 1. Oblique Mercator projection of western Cordillera about preferred Sierra Nevada–North American Euler pole of Argus and Gordon (2001). Direction of instantaneous Sierra Nevada–North American motion is vertical everywhere in projection. Strike-slip faults of Walker Lane belt are subparallel to Sierra Nevada–North American motion; normal faults strike ~45° clockwise of that motion; and major graben and zones of extension are located in areas where locus of deformation along eastern Sierra is steps eastward in releasing geometry (Quaternary faults modified from Jennings, 1994). MTJ—Mendocino triple junction; SEGP—subducted southern edge of Gorda plate; CB—Cape Blanco; ICF—Inks Creek fold belt; HC—Hat Creek graben; A—Lake Almanor structural basin; MV—Mohawk Valley; HL—Honey Lake fault; T—Lake Tahoe basin; C—Carson Valley; LV—Long Valley; SNFFS—Sierra Nevada frontal fault system; I—Independence fault; OV—Owens Valley; IWV—Indian Wells Valley; ECSZ—Eastern California shear zone; DV—Death Valley.

LATE CENOZOIC FAULTING ALONG THE EASTERN MARGIN OF THE SIERRAN MICROPLATE

Previous workers have recognized that the eastern margin of the Sierra Nevada and adjacent Walker Lane belt (Fig. 1) compose a tectonically active domain that is structurally and kinematically distinct from the Basin and Range to the east (Wright, 1976; Stewart, 1988). Geodetic data indicate that ~11 mm/yr of northwest dextral shear (~22% of Pacific–North American plate motion) is distributed across strike-slip and normal faults in the central Walker Lane belt at lat 37.5°N (Dixon et al., 2000; also see Wakabayashi and Sawyer, 2001, for estimates of slip rates on individual faults in the Walker Lane belt). We assess modern deformation in this region by examining the orientations and kinematics of Quaternary faults in a reference frame defined by the Sierra Nevada–North American Euler pole of Argus and Gordon (2001) (Fig. 1). We focus specifically on the major active faults that compose the eastern tectonic margin of the Sierran microplate.

At the southern end of the Sierra Nevada, the dextral Little Lake and Airport Lake faults in Indian Wells Valley make up the major tectonic boundary along the southeastern margin of the Sierran microplate (Unruh et al., 2002), and are subparallel to Sierra Nevada–North American motion (Fig. 1). Dextral shear on these structures is transferred northward in a releasing stepover across the Coso Range to the Owens Valley fault, producing distributed crustal extension in the Coso Range (Unruh et al., 2002). The Owens Valley fault strikes clockwise of local Sierra Nevada–North American motion (Fig. 1) and thus has a releasing geometry relative to that motion. Coseismic slip on the Owens Valley fault during the 1872 Owens Valley earthquake was predominantly dextral with a component of normal displacement (Beanland and Clark, 1994), consistent with accommodation of Sierra Nevada–North American motion via oblique right-normal slip.

Quaternary deformation along the eastern margin of the Sierran microplate north of Owens Valley is accommodated by a series of normal faults that compose the classic Sierra Nevada range front system (Bateman and Wahrhaftig, 1966). The southernmost fault in this system may be the Independence fault west of Owens Valley (Fig. 1). Rather than a continuous, if segmented, system of faults that strike parallel to the average trend of the range front, the Sierran frontal faults exhibit a left-stepping en echelon pattern, with individual fault segments oblique to the range front (Bateman and Wahrhaftig, 1966; Wakabayashi and Sawyer, 2001). The trend of the physiographic Sierran range front is subparallel to Sierra Nevada–North American motion (Fig. 1), and the left-stepping fault segments strike ~45° clockwise of that trend. Similar patterns of en echelon normal faults have been observed in analog models of releasing stepovers in dextral wrench systems (e.g., Dooley and McClay, 1997). We interpret the orientation and left-stepping geometry of the normal faults as evidence that they have formed in a transcurrent regime and primarily accommodate Sierra Nevada–North American motion.

At ~lat 38.5°N, the Sierran frontal fault system splits into two branches. One branch passes to the northeast through Lake Tahoe and is represented by normal faults that form the Tahoe structural basin. Displacement along this branch is transferred to the northwest-striking Mohawk Valley fault, a dextral fault subparallel to Sierra Nevada–North American motion that forms the eastern margin of the rigid Sierran microplate at this latitude (Wakabayashi and Sawyer, 2001; Fig. 1). The second branch passes to the northeast through Carson Valley, and primarily is represented by the Genoa fault bordering the eastern front of the Carson Range. We interpret the branching of the Sierran frontal fault system at 38.5°N to be a discrete right step along the eastern edge of the Sierran microplate, where the locus of active deformation is transferred eastward in a releasing geometry relative to Sierra Nevada–North American motion (Fig. 1). The Tahoe basin and Carson Valley are extensional features associated with this releasing step.

The Mohawk Valley fault can be traced northwest to the southern edge of the Lake Almanor basin, where the strike of Quaternary faults turns abruptly to the north. The major structures along this trend are the Almanor structural depression and the north-northwest–striking Hat Creek graben (Fig. 1) (Wakabayashi and Sawyer, 2000). In detail, normal faults accommodating extension along this trend have a left-stepping, en echelon pattern similar to that of the Sierra Nevada frontal fault system.

Unruh et al. (1996b) observed that a component of deformation along the eastern margin of the northern Sierra Nevada may step westward across the crest of the range. This is a left step relative to average Sierra Nevada–North American motion, and in this kinematic framework localized crustal shortening is predicted. Evidence for Quaternary shortening in the putative left-stepover region is the east-northeast–trending Inks Creek fold system at the northwestern margin of the Sierra Nevada (Harwood and Helley, 1987), and northeast-striking reverse faults (Fig. 1). This deformation may accommodate a small component of convergence between the Sierran microplate and the Klamath Mountains (Unruh, 2000).

Residual Global Positioning System (GPS) velocities (corrected for elastic strain on the Cascadia subduction zone) indicate that crust between the Mendocino triple junction and Cape Blanco is moving northwest relative to North America, subparallel to Sierra Nevada–North American motion (Miller et al., 2001). In contrast, residual GPS velocities in coastal Oregon north of Cape Blanco are directed north to north-northeast, consistent with the hypothesis that the Cascadia forearc region moves northward as an independent forearc sliver (Wells et al., 1998). We suggest that the Walker Lane, here defined as a belt of distributed deformation accommodating Sierra Nevada–North American motion, extends obliquely across northern California and southern Oregon and ultimately feeds slip into the southern Cascadia forearc south of Cape Blanco (Fig. 1). It is interesting to note that the southern edge of the subducting Gorda plate, the Blanco fracture zone, and a dextral shear zone in the interior of the Gorda plate (Wilson, 1989) are subparallel to Sierra Nevada–North American motion.

SEISMOTECTONICS OF THE WALKER LANE BELT

We inverted groups of earthquake focal mechanisms for components of reduced strain-rate tensors to characterize seismogenic deformation in Walker Lane belt east of the Sierra Nevada. A description of the instrumental seismicity in this region can be found in VanWormer and Ryall (1980). Earthquake data for this study were obtained from the Northern California Seismic Network, the Southern California Seismic Network, and the University of Nevada. Phase data for Walker Lane events for the period 1970 to 1995 were obtained from catalogs maintained by these institutions. Single-event focal mechanisms were calculated for selected earthquakes using the program FPFIT (Reasenberg and Oppenheimer, 1985).

We used a micropolar continuum model (Twiss et al., 1993; Twiss and Unruh, 1998) as a basis for inverting seismic P and T axes derived from the focal mechanisms to obtain the components of a reduced strain-rate tensor for a given group of earthquakes (for a complete description of the analytical approach, see Unruh et al., 1996a). The best-fit model obtained from the micropolar inversion includes the orientations of the principal strain rates ($d_1 > d_2 > d_3$; lengthening positive); a scalar parameter (D) that is formed by a ratio of the differences in the principal strain rates, and that characterizes the shape of the strain-rate ellipsoid; a scalar parameter (W) that characterizes the relative vorticity of rigid, fault-bounded blocks about an axis parallel to d_2; and a measure of the misfit between the best-fit model and the data (Unruh et al., 1996a) (Table DR1[1]).

[1]GSA Data Repository item 2003039, Table DRI, kinematic inversions of focal mechanisms from the Walker Lane belt, is available upon request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

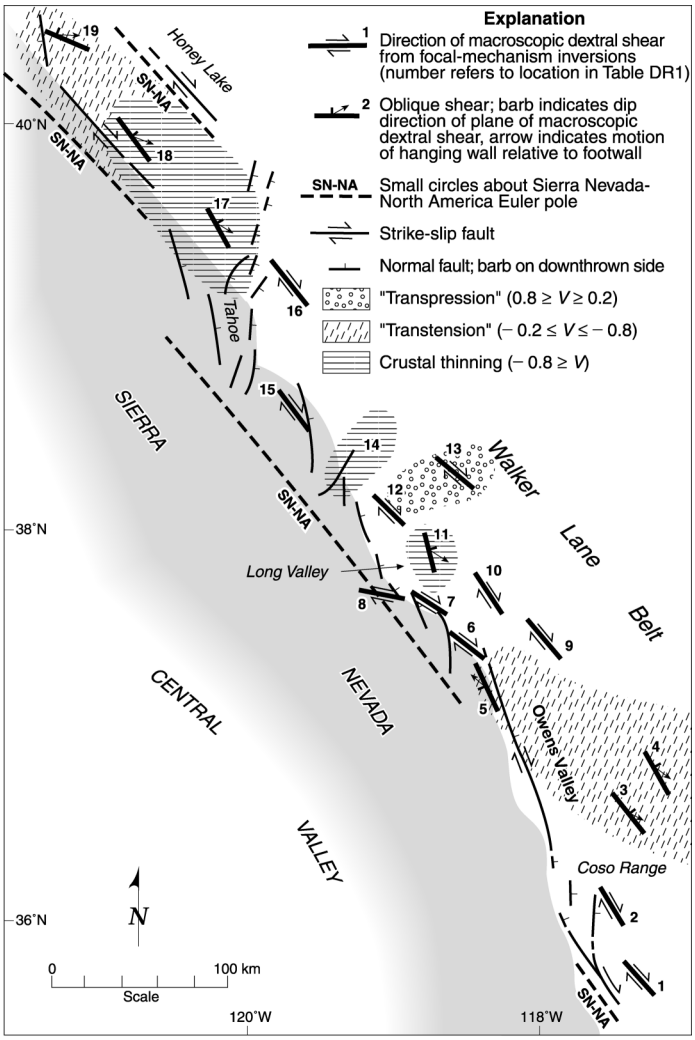

Figure 2. Directions of macroscopic dextral shear in Walker Lane belt derived from kinematic inversions of focal mechanisms (Table DR1; see footnote 1). Numbers refer to inversion results from geographic domains listed in Table DR1; patterns show relative component of vertical deformation (parameter *V*, Table DR1). With primary exception of southern Long Valley caldera, macroscopic dextral shear in Walker Lane is subparallel to small circles about Sierra Nevada–North American Euler pole (bold dashed lines). 1—Ridgecrest area; 2—Coso Range; 3—Saline Valley; 4—Death Valley–Panamint Mountains; 5—Round Valley; 7—Hilton Creek; 8—southern Long Valley caldera; 9—Deep Spring Valley; 10—Chalfant Valley; 11—Adobe Valley; 12—northern Mono Basin; 13—Excelsior Mountains; 14—Bridgeport Valley; 15—Double Spring Flat; 16—Carson Range; 17—Truckee area; 18—Mohawk Valley; 19—Lake Almanor.

To characterize the net vertical deformation accommodated by the earthquakes, we calculate the ratio V (Unruh et al., 2002) of the vertical deviatoric deformation rate to the maximum deformation rate. Following Lewis et al. (2003), we interpret values of V as follows: $1 \geq V \geq 0.8$, net crustal thickening; $0.8 \geq V \geq 0.2$, oblique crustal thickening (i.e., transpression); $0.2 \geq V \geq -0.2$, horizontal shearing; $-0.2 \geq V \geq -0.8$, oblique crustal thinning (i.e., transtension); and $-0.8 \geq V \geq -1$, net crustal thinning. Values of $-1 > V > -2$ indicate nonplane strain crustal thinning with extension in two horizontal directions (i.e., flattening). These values provide a simple (if arbitrary) means of distinguishing transpressional and transtensional deformations from transcurrent shearing.

The majority of the inversion results indicate that seismogenic deformation in the Walker Lane belt accommodates horizontal shearing and oblique thinning of the crust (Table DR1 [see footnote 1]; Fig. 2). This result includes areas of pronounced late Cenozoic normal faulting such as the central Coso Range, the Sierran frontal fault system south of Long Valley, Chalfant Valley, and the Carson Range (Fig. 2). As noted by Unruh et al. (2002), normal faults in the Coso Range strike perpendicular to the maximum extensional principal strain rate (d_1) and exhibit a left-stepping geometry consistent with formation in a dextral regime. Similar relations are present along the Sierran frontal fault system (Fig. 1), which has long been assumed to accommodate Basin and Range–style crustal extension. Pronounced crustal thinning (as distinguished from transtension) occurs locally rather than regionally throughout the Walker Lane belt (e.g., Truckee area, Mohawk Valley, Bridgeport Valley). Seismogenic deformation in the Excelsior Mountains region is slightly transpressional, suggesting that local restraining steps may be present in the transfer of dextral shear among structures in the eastern Walker Lane belt (Table DR1 [see footnote 1]; Fig. 2).

To compare seismogenic strain to Sierra Nevada–North American motion, we derived the orientation of planes of maximum dextral shear rate from the strain-rate tensors (Table DR1; see footnote 1). The plane of maximum dextral shear rate is parallel to the d_2 axis and bisects the orthogonal d_1 and d_3 axes in the northwest and southeast quadrants. The direction of maximum resolved shear in this plane is orthogonal to the d_2 axis. The results (Fig. 2) indicate that macroscopic dextral shear associated with seismicity in the Walker Lane belt is subparallel to Sierra Nevada–North American motion. In general, the obliquity of dextral shear to Sierra Nevada–North American motion is greatest in areas dominated by vertical crustal thinning. The most significant departure from this regional trend is in the southern Long Valley caldera, where the direction of macroscopic dextral shear turns sharply to the west (Fig. 2). Local counterclockwise rotation of dextral shear in Long Valley relative to regional trends also is observed geodetically (Savage et al., 1987); we attribute this to local stresses and deformation associated with intrusion and movement of magma beneath the caldera.

CONCLUSIONS

Mixed patterns of active strike-slip and normal faulting in the Walker Lane belt bordering the Sierran microplate can be reconciled in a kinematic framework of distributed dextral shear parallel to Sierra Nevada–North American motion. Normal faults along the eastern Sierran range front have long been interpreted to accommodate uplift of the range and relative subsidence of the basins to the east (e.g., Bateman and Wahrhaftig, 1966). Although there may be an earlier Neogene history of horizontal extension normal to the range front (e.g., Monastero et al., 2002), we suggest that these structures presently accommodate northwest translation of the Sierra Nevada, and that graben like the Tahoe basin are a consequence of releasing steps along the margin of the microplate. The classic Sierran frontal fault system can be viewed as a 500-km-long releasing stepover between the dextral Airport and Little Lake faults to the south, and the dextral Mohawk Valley fault to the north (Fig. 1). Our results support the interpretation that Walker Lane deformation primarily is driven by distant plate-boundary forces rather than locally derived buoyancy forces (Sonder and Jones, 1999; Thatcher et al., 1999).

In contrast to the transtensional kinematics east of the microplate, some Sierra Nevada–North American motion appears to step westward across the crest of the northern Sierra Nevada in a restraining geometry, driving local crustal shortening in the northern Sacramento Valley between the Sierran microplate and Klamath Mountains (Fig. 1). Late Cenozoic deformation of the Gorda plate inferred from magnetic isochrons (Wilson, 1989) may reflect progressive interaction of the northern Sierran microplate and Walker Lane belt with the southern Cascadia forearc region during the past several million years.

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