Seismogenic deformation between the Sierran microplate and Oregon Coast block, California, USA

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ABSTRACT

The Sierran microplate is a northwest-translating block entrained in distributed motion east of the Pacific plate. To the north, the Oregon coast block (OCB) moves northward within the hanging wall of the Cascadia subduction zone, above the obliquely converging Juan de Fuca plate. Analysis of GPS velocity data indicates that relative motion between the rigid Sierran and OCB microplates is characterized by several millimeters per year of dextral shear directed ~N70°W, which is distinct from and counterclockwise to macroscopic dextral shear in the Walker Lane east of the Sierran microplate. We present a new analysis of focal mechanisms from small earthquakes in an 80-km-wide zone that spans the geodetically defined Sierran-OCB boundary to evaluate patterns of distributed deformation. We find that the direction of macroscopic dextral shear in this region is parallel to Sierran-OCB motion derived from GPS data. The seismogenic deformation is consistent with postulated dextral shear within an incompletely studied west-northwest–trending zone of faults and lineaments that traverses the northern Sierra Nevada; the faults and lineaments terminate westward against Quaternary folds in the northern Sacramento Valley. Active deformation at the Sierran-OCB boundary accommodates the relative motion of the bounding microplates and probably does not represent discrete transfer of Walker Lane motion to the Cascadia subduction zone in a restraining left step across the northern Sierra and Sacramento Valley.

INTRODUCTION

Large-scale deformation in California and the Pacific Northwest (USA) adjacent to the oceanic plate boundaries is dominated by microplate translation and rotation (Fig. 1). The Sierra Nevada–Central Valley (Sierran) microplate, which comprises much of central California, is bounded on the west by the Pacific coast block and moves ~11–13 mm/yr northwest with respect to stable North America (Argus and Gordon, 1991, 2001). To the north, the Oregon coast block (OCB) is above the Cascadia subduction zone and the obliquely convergent Juan de Fuca plate, and generally is moving north with respect to stable North America (Wells et al., 1998; Wells and McCaffrey, 2013). The Sierran and OCB microplates move approximately subparallel to tractions across their western boundaries imparted by the oceanic plates (McCaffrey et al., 2013; Fig. 2). The motion of the Sierran microplate relative to stable North America (S-NA) is described by counterclockwise rotation about an Euler pole located off the coast of southwestern California (Argus and Gordon, 1991, 2001), whereas OCB–North American motion (OCB-NA) is characterized by clockwise rotation about an Euler pole near the Oregon-Idaho border at lat ~45° N (McCaffrey et al., 2013) (Fig. 1). The Walker Lane and northern Basin and Range Province are east of these microplates and accommodate additional distributed deformation relative to stable North America (Wells and Simpson, 2001; Hammond and Thatcher, 2007; Fig. 1).

Given that the Sierran microplate and OCB move as rigid blocks, and that their motions relative to North America are described by distinct Euler poles with opposite senses of rotation (Fig. 1), differential motion between the blocks should produce observable deformation. In this paper we analyze earthquake focal mechanisms in northern California to evaluate seismogenic deformation across the geodetically observed Sierran microplate–OCB (S-OCB) boundary and compare it to their predicted relative motion.

NORTHERN TERMINATION OF THE SIERRAN MICROPLATE AND WALKER LANE

The south to north transition from the Sierran microplate to the OCB, and the northeastward extent of related deformation, can be discerned in
patterns of crustal motion measured by GPS geodesy. When GPS data are viewed in an oblique Mercator projection about the S-NA Euler pole (Fig. 2), velocities in the Sacramento Valley and northern Sierra are parallel to S-NA motion, indicating that those stations are on the Sierran microplate. To the north, GPS velocities rotate clockwise to more north azimuths near lat 40.5°N (Figs. 1 and 2; also see McCaffrey, 2003). With corrections for elastic strain accumulation along the Cascadia subduction zone, GPS velocities in southwestern Oregon north of this point are described primarily by clockwise rotation about the OCB-NA pole (Hammond and Thatcher, 2005; Williams et al., 2006; McCaffrey et al., 2013). The clockwise rotation of velocities thus marks the transition from S-NA motion to OCB-NA motion in northwestern California, and the kinematic boundary between the two microplates.

The pattern of clockwise rotation away from S-NA-parallel motion continues eastward into the Cordilleran approximately along a northeast-trending boundary that extends from near Lassen Peak toward a region where McCaffrey et al. (2013) estimated the OCB-NA Euler pole (or poles, for rotating subblocks in the Pacific Northwest) to be located (Fig. 1). Elastic dislocation modeling suggests that GPS velocities east of the Sierra, and in the backarc region of Oregon, are not significantly affected by the locked Cascadia subduction zone (Lewis et al., 2003, his figure 2; Williams et al., 2006); if this is correct, then the clockwise rotation of velocity azimuths in the backarc region in Figure 2 reflects a kinematic transition from S-NA-parallel motion. The OCB-NA pole in Figure 1 is indicated with a white circle to reflect uncertainty in its precise location, as well as uncertainty about whether the forearc and backarc regions of Oregon and Washington rotate about a single pole or multiple poles (see McCaffrey et al., 2013). Despite this uncertainty, the shift from S-NA-parallel motion across the northeast-trending boundary to clockwise rotation about a proximal pole to the east is relatively well defined by GPS data in northern California and southeastern Oregon. We interpret that the northeast-trending boundary generally represents the northern termination of distributed deformation in the Walker Lane and the northern Basin and Range, and a transition to rigid block rotation to the northwest (Fig. 1). Southeast of this boundary, the Walker Lane and northern Basin and Range open in a fan-like manner approximately about the OCB-NA pole, facilitating strain compatibility east of the microplates.

Although the Sierran and OCB microplates generally move as rigid blocks, they are instantaneously translating in different directions and rates on opposite sides of their shared boundary, and therefore there must be deformation between them to accommodate the differential motion. Using GPS data, R. McCaffrey (2016, personal commun.) derived an S-OCB Euler pole that predicts that the northern Sacramento Valley moves ~5 mm/yr toward N70°W relative to the southern Klamath Mountains in Oregon (see Fig. DR5 in the GSA Data Repository1). This predicted motion between the microplates is similar to, if slightly clockwise to, dextral shear along the east-west–trending Mendocino fracture zone to the west, consistent with the hypothesis that tractions from the oceanic plates are major drivers of microplate motion.

These observations lead to testable predictions. Deformation in the Walker Lane east of the Sierra Nevada microplate is characterized by distributed northwest-directed transtensional dextral shear that is subparallel to S-NA motion (Fig. 2; Unruh et al., 2003). Within the S-OCB boundary, however, the direction of macroscopic shear should trend approximately west-northwest, parallel to relative S-OCB motion (Fig. 2) and counterclockwise to S-NA-parallel motion in the northern Walker Lane.

SEISMOTECTONIC ANALYSIS

Approach

We analyzed focal mechanisms from regional seismicity to evaluate distributed brittle deformation across the S-OCB boundary. Earthquakes recorded by the Northern California Seismic Network (NCSN, http://ncedc.org/ncsn/) were relocated using the double-difference methodology of Waldhauser and Ellsworth (2000) and Waldhauser (2001). Region-specific one-dimensional (1-D) velocity models were adapted from the Thurber et al. (2009) 3-D velocity model of northern California (Fig. DR1; see the Data Repository for additional detail). Single-event focal mechanisms for the relocated earthquakes were calculated using the phase polarities from the NCSN catalog and the hypocentral locations and takeoff angles were calculated from the double-difference solutions. The focal mechanisms were determined using the program FFPFIT (Reasenberg and Oppenheimer, 1985), which determines the best-fit double couple solution to the pattern of radiated seismic energy.

We used a micropolar continuum model for distributed brittle deformation (Twiss et al., 1993; Twiss and Unruh, 1998) as a basis for inverting seismic P and T axes from groups of focal mechanisms to derive a reduced deformation rate tensor. For individual groups of earthquakes and their focal mechanisms, the inversion provides five parameters characterizing the deformation geometry: three Euler angles that define the

1GSA Data Repository item 2017121, supplemental information about earthquake relocation, kinematic inversion results, and differential S-OCB motion from GPS data, is available online at http://www.geosociety.org/datarepository/2017/or on request from editing@geosociety.org.
orientations of the principal strain rates (i.e., $d_1 > d_2 > d_3$; lengthening reckoned positive); a deformation-rate parameter ($D$) formed by a ratio of the differences in the principal strain rates that characterizes the shape of the strain rate ellipsoid; and a scalar parameter ($W$) that characterizes the relative vorticity of rigid, fault-bounded blocks about an axis parallel to the intermediate principal strain rate axis $d_2$. For simplicity of discussion, the strain rates in the micropolar model are herein assumed to be equivalent to incremental strains. An additional scalar parameter $V$, which characterizes the net vertical deformation, is derived from the components of the reduced strain-rate tensor. Positive values of $V$ indicate net crustal thickening, negative values indicate net crustal thinning, and a value of zero indicates horizontal plane strain (Lewis et al., 2003).

**Results**

The strain geometry for individual spatial domains is summarized in Figure 3 (detailed inversion results are provided in Table DR1 in the Data Repository). The heterogeneous deformation in the region centered on the northern Sacramento Valley and surrounding parts of the Sierra Nevada and Klamath Mountains generally is characterized by counterclockwise rotation of the principal strains relative to the Walker Lane and backarc region east of Mount Shasta (Fig. 3). This region approximately straddles the S-OCB transition in the velocity field (Fig. 2). To assess systematic variations in deformation kinematics, we derived the plane of maximum dextral shear for domains where the inversion results indicate that the principal extensional and shortening strains are subhorizontal (i.e., the deformation is approximately a horizontal plane strain). As shown in Figure 2, subvertical planes of maximum resolved dextral shear in the northern Sacramento Valley trend approximately WNW–ESE, subparallel to differential S-OCB motion indicated by the GPS data (Fig. DR5) and counterclockwise to northwest dextral shear in the Walker Lane to the southeast (Unruh et al., 2003) and in the backarc region of southern Oregon east of Mount Shasta.

**DISCUSSION**

The zone of approximately WNW–ESE dextral shear includes faults of the Sierra-Cascade boundary zone (SCBZ; Figs. 2 and 3; see Sawyer,
and the northeast-trending Inks Creek folds (Harwood and Helley, 1987; Angster et al., 2015). Many of these structures are incompletely studied, and the seismicity inversions provide some insight into their kinematics and possible role in accommodating S-OCB motion. For example, dextral separation on the N70°W-striking faults of the SCBZ, which was interpreted by Sawyer (2013) primarily from reconnaissance geomorphic analysis of river canyons crossed by the structures, is consistent with inversion results from the northern part of the zone (domain SB22 in Fig. 3) and would directly accommodate differential S-OCB motion. The SCBZ faults terminate westward against the blind Red Bluff reverse fault and the northeast-trending Inks Creek folds in the northern Sacramento Valley (Figs. 2 and 3). The contractual structures are oriented counterclockwise to the west-northwest direction of macroscopic dextral shear (a restraining geometry), at high angles to the maximum shortening strain, and exhibit a right-stepping pattern consistent with transtension, as indicated by the focal mechanism inversions (Fig. 3; Table DR1).

These relations suggest that the SCBZ faults and Inks Creek folds are major map-scale structures of the S-OCB boundary. The activity of these structures is driven by relative S-OCB motion, which is independent of and distinct from distributed S-NA-parallel motion in the Walker Lane. It was suggested (Unruh et al., 2003) that late Cenozoic shortening in the northern Sacramento Valley might be driven by a left-restraining transfer of some dextral Walker Lane shear to the southern Cascadia subduction zone. Although we cannot preclude this as a possible contributing factor to activity of the Inks Creek structures, the deformation can be explained by differential S-OCB motion, and a discrete stepover from the Walker Lane to Cascadia is not required to account for localized shortening in the northern Sacramento Valley.

CONCLUSIONS

GPS geodesy and patterns of seismogenic deformation indicate that the transition from counterclockwise rotation of the Sierran microplate to clockwise rotation of the OCB (relative to North America) occurs in an ~80-km-wide zone about lat 40.5°N. Differential motion between the microplates is accommodated by distributed west-northwest-directed dextral shear in the northern Sierra Nevada and localized transtension in the northern Sacramento Valley. The S-OCB boundary is spatially associated with the Mendocino triple junction, and the northern termination of the Walker Lane and northern Basin and Range Province. The location and orientation of these boundaries facilitate compatibility with the transition from distributed northwest dextral shear east of the Sierran microplate to clockwise rotation of rigid blocks in the Pacific Northwest.

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