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Persistent slip rate discrepancies in the eastern California (USA) shear zone

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ABSTRACT

Understanding fault slip rates in the eastern California shear zone (ECSZ) using GPS geodesy is complicated by potentially overlapping strain signals due to many sub-parallel strike-slip faults and by inconsistencies with geologic slip rates. The role of fault system geometry in describing ECSZ deformation may be investigated with total variation regularization, which algorithmically determines a best-fitting geometry from an initial model with numerous faults, constrained by a western United States GPS velocity field. The initial dense model (1) enables construction of the first geodetically constrained block model to include all ECSZ faults with geologic slip rates, allowing direct geologic-geodetic slip rate comparisons, and (2) permits fault system geometries with many active faults that are analogous to distributed interseismic deformation. Beginning with 58 ECSZ blocks, a model containing 10 ECSZ blocks is most consistent with geologic slip rates, reproducing five of 11 within their reported uncertainties. The model fits GPS observations with a mean residual velocity of 1.5 mm/yr. Persistent geologic-geodetic slip rate discrepancies occur on the Calico and Garlock faults, on which we estimate slip rates of 7.6 mm/yr and <2 mm/yr, respectively, indicating that inconsistencies between geology and geodesy may be concentrated on or near these faults and are not due to pervasive distributed deformation in the region. Discrepancies may in part be due to postseismic relaxation following the A.D. 1992 M_w 7.3 Landers and 1999 M_w 7.1 Hector Mine earthquakes. Otherwise, resolving geologic-geodetic discrepancies would require as much as 11.4 mm/yr of off-fault deformation within <10 km of the main ECSZ faults, with ~5 mm/yr concentrated near the Calico fault.

INTRODUCTION

The eastern California shear zone (ECSZ) in southeastern California (USA) consists of a network of primarily northwest-striking strike-slip faults accommodating ~25% of Pacific–North America plate motion (Fig. 1A) (e.g., Sauber et al., 1994; Dixon et al., 2003).

Understanding the partitioning of tectonic motion across ECSZ faults is complicated by apparently large discrepancies between geologic and geodetic slip rate estimates. Geologically determined individual fault slip rates in the eastern Mojave Desert range from <0.4 mm/yr to 1.8 mm/yr, with a cumulative fault displacement rate of <8 mm/yr across the region (e.g., Oskin et al., 2008). Geodetic observations suggest regional displacement rates as high as ~18 mm/yr (e.g., Spinler et al., 2010). This discrepancy continues north of the Garlock fault on the Owens Valley and Death Valley faults, with individual geologic slip rates consistently <3 mm/yr (Lee et al., 2001; Frankel et al., 2007b) and geodetic rates as high as ~13 mm/yr (e.g., Dixon et al., 2003). On the east-west–striking left-lateral Garlock fault, however, geodetic slip rates are lower than geologic rates (0–3 mm/yr geodetic relative to 5–7 mm/yr geologic) (McGill and Sieh, 1993; Becker et al., 2005; Meade and Hager, 2005; Ganev et al., 2012).

Higher geodetic slip rate estimates for the northwest-striking faults of the ECSZ have often been attributed to off-fault permanent deformation (e.g., Herbert et al., 2014; Dolan and Haravitch, 2014). Here, we use "off-fault" deformation specifically to refer to deformation unrelated to earthquake cycle processes on faults.

We test the possibility that what has been considered off-fault or distributed deformation may be well described by slip on faults commonly not included in geodetic models. To do so, we examine rigid block models in which geometries are determined using total variation regularization (TVR) (Rudin et al., 1992; Chambolle, 2004). Beginning with 58 blocks in the ECSZ, we identify a model geometry containing 10 blocks that fits GPS observations well, but reproduces only five of 11 geologic slip rates. The GPS derived slip rates result in ~18 mm/yr of cumulative displacement across the ECSZ and identify persistent discrepancies with geologic slip rates on the Calico and Garlock faults.

BLOCK MODEL AND TOTAL VARIATION REGULARIZATION

Geodetic observations may be interpreted using block models, in which the upper crust is divided into microplates bounded by faults (e.g., Meade and Hager, 2005). Typically, the number and geometry of microplates are defined by boundaries representing a limited subset of mapped faults. Previous southern California block models contain between two (Chuang and Johnson, 2011) and seven (Loveless and Meade, 2011) ECSZ blocks. Here we include many possible faults in a dense array of blocks (Fig. 1B; Fig. DR1 in the GSA Data Repository[1]) and estimate the boundaries at which strain is localized based on observations of interseismic deformation with a TVR algorithm (Rudin et al., 1992; Chambolle, 2004). Applied to three-dimensional spherical block models, TVR produces solutions in which many blocks have identical rotation vectors; faults bounding adjacent blocks with identical rotation vectors have slip rates exactly equal to zero, localizing fault slip on the boundaries of aggregated larger blocks (Evans et al., 2015; see the Data Repository for details on block modeling methodology and setup).

We apply TVR to block rotations within the ECSZ; block rotations outside of the ECSZ are subject to weighted least squares. This maintains constant block geometry outside of the region of interest and allows fault system geometry within the ECSZ to vary. Slip rates outside of the ECSZ are not fixed, ensuring kinematic consistency across the plate boundary (Minster and Jordan, 1978; Humphreys and Weldon, 1994).

This is the first block model to include all ECSZ faults in the UCERF3 geologic slip rate catalog of Dawson and Weldon (2013). Geologic slip rates are not included as constraints, so we may use them to test the slip rate predictions of the block model. We compare our model results with geologic slip rates at 11 sites (Fig. 1B; Table 1).

We constrain deformation with horizontal interseismic velocities at 1691 locations from a combined velocity field of the western United States (Loveless and Meade, 2011, their Data Repository item 2011305) to maintain realistic slip rates outside of the study area (Fig. 1C; Fig. DR1). The combined velocity field spans the

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[1]GSA Data Repository item 2016225, additional description of block model selection, Table DR1, and Figures DR1–DR5, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org.

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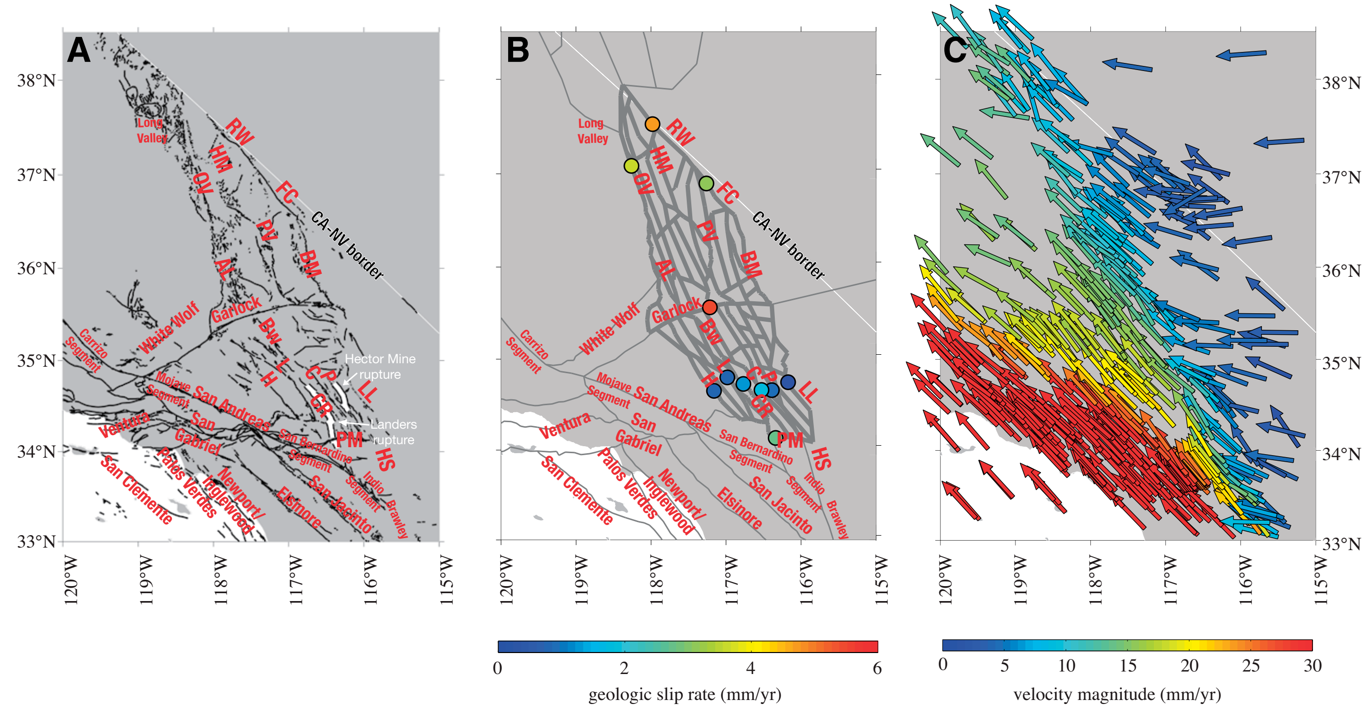

Figure 1. A: Fault map of southern California (USA). Fault traces from Jennings (1994). Selected faults and regions are labeled. Fault abbreviations: AL—Airport Lake; BM—Black Mountain; Bw—Blackwater; C—Calico; CR—Camp Rock; FC—Furnace Creek; H—Helendale; HM—Hunter Mountain; HS—Hidden Springs; L—Lenwood; LL—Ludlow; OV—Owens Valley; P—Pisgah; PM—Pinto Mountain; PV—Panamint Valley; RW—Red Wall Canyon. Surface ruptures of the A.D. 1992 M_w 7.3 Landers and 1999 M_w 7.1 Hector Mine earthquakes are in white. CA—California; NV—Nevada. B: Input geometry of southern California blocks. Geologic slip rate magnitudes are shown in colored circles. Total variation regularization was applied to blocks bounded by bold faults. C: GPS velocities from combined western USA velocity field relative to fixed North America (Loveless and Meade, 2011), colored by velocity magnitude.

TABLE 1. EASTERN CALIFORNIA SHEAR ZONE GEOLOGIC SLIP RATES

Fault segment	Geologic rate (mm/yr)	Reference
Pinto Mountain	–2.8 ± 2.5	Anderson, 1979; Petersen and Wesnousky, 1994
Camp Rock	≤1.4 ± 1.4	Oskin et al., 2008
Death Valley–Furnace Creek	3.1 ± 0.4	Frankel et al., 2007b
Garlock	–5.3 +1/–2.3	Ganev et al., 2012
Helendale	0.8 ± 0.8	Oskin et al., 2008
Ludlow	≤0.4 ± 0.4	Oskin et al., 2008
Owens Valley	3.7 ± 1.8	Frankel et al., 2007b
Pisgah	1.0 ± 0.5	Oskin et al., 2008
Death Valley–Red Wall Canyon	4.5 +1.6/–1.4	Frankel et al., 2007a
Lenwood	≤0.8 ± 0.4	Oskin et al., 2008
Calico	1.8 ± 0.7	Oskin et al., 2007

years A.D. 1986–2011 in southern California (Shen et al., 2011; Loveless and Meade, 2011), and stations identified as having significant postseismic signal due to the 1992 M_w 7.3 Landers and 1999 M_w 7.1 Hector Mine earthquakes were removed (Shen et al., 2011).

TVR BLOCK MODEL RESULTS

Beginning with a densely populated model with 86 blocks (58 ECSZ blocks), only 38 blocks (10 ECSZ blocks) are required to fit GPS observations with mean residual velocity (MRV) of 1.5 mm/yr (Fig. 2). Out of 50 models considered, this model represents the best agreement with geologic slip rates, with five slip rates that agree within uncertainty (Fig. 2A; see the Data Repository for additional details on model selection).

We estimate 17.6 mm/yr of cumulative slip across the eastern Mojave faults, with 7.6 mm/yr concentrated on the Calico fault. This is at the upper end of previous geodetic estimates of 15–18 mm/yr (Spinler et al., 2010; Chuang and Johnson, 2011; McGill et al., 2015), higher than relative plate velocity of 12 mm/yr between the Sierra block and North America (e.g., Sauber et al., 1994), and about three times higher than the <6.2 ± 1.9 mm/yr observed in the geologic record (Oskin et al., 2008), for a total geologic-geodetic discrepancy of 11.4 mm/yr.

The preferred model reproduces five geologic slip rates in the ECSZ within reported uncertainties (Fig. 3). These are: the Lenwood, Pisgah, and Pinto Mountain faults and the Red Wall Canyon and Furnace Creek segments of the Death Valley fault zone. We estimate four slip rates higher than geologic rates (Ludlow, Helendale, Camp Rock, and Calico faults) and two rates lower than geologic rates (Garlock and Owens Valley faults). The largest discrepancies occur on the Calico fault,7.6 mm/yr compared with the 1.8 ± 0.3 mm/yr geologic rate (Oskin et al., 2007); and on the Garlock fault, 0.3 mm/yr geodetic versus 5.3 +1/–2.3 mm/yr geologic (Ganev et al., 2012). Estimated slip rates in the eastern Mojave Desert are consistent with those estimated along a dense geodetic profile of permanent and campaign GPS stations across the San Andreas fault and eastern Mojave Desert (McGill et al., 2015). As in this study, McGill et al. (2015) identify the Calico as the fastest ECSZ fault.

Although not the focus of this work, we estimate slip rates of 8–29 mm/yr on the San Andreas fault (Fig. 2; Table DR1; Fig. DR2). The Hidden Springs fault (e.g., Spinler et al., 2010) transfers 5 mm/yr of slip directly from the Brawley seismic zone to the Calico fault. Inclusion of this fault is speculative, as it is only mapped for 20 km. However, the northern projection of the mapped trace is co-located with a gradient in the geodetic velocity field identified by cluster analysis (Thatcher et al., 2016).

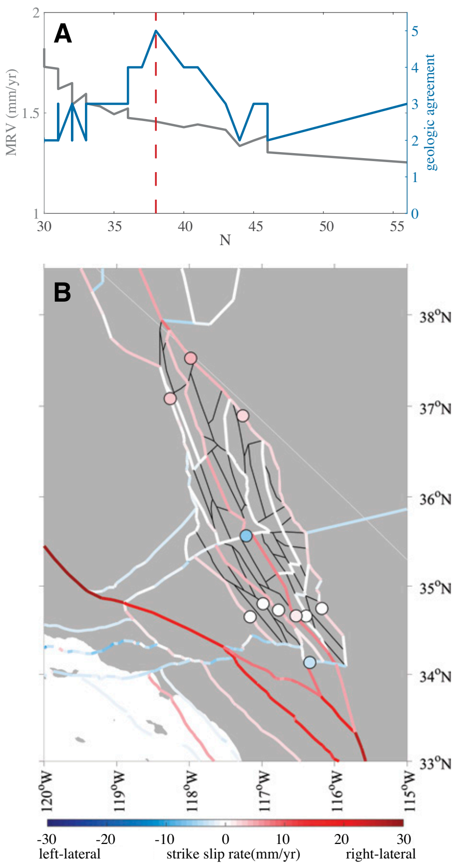

Figure 2. A: Solution behavior for a suite of 50 models containing between 30 and 86 blocks. As number of unique blocks (N) increases, mean residual velocity (MRV) decreases (gray line). Blue line shows number of estimated slip rates that agree with respective geologic slip rates within reported uncertainties. Preferred model is shown with dashed red line. B: Strike-slip rates from preferred total variation regularization solution. Black faults have estimated slip rate of exactly 0 mm/yr. Geologic slip rates are shown in colored circles in same color scale as fault slip rates.

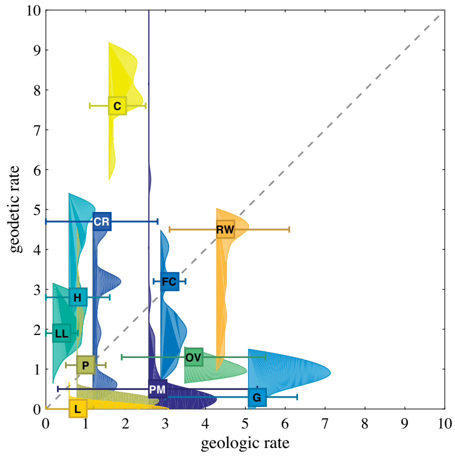

Figure 3. Comparison of geologic slip rates and geodetic slip rates from this study. Preferred model is highlighted with colored squares. Abbreviations as in Figure 1; G—Garlock. Horizontal error bars represent reported uncertainty in geologic slip rates. Vertical distributions represent distribution of estimated slip rates from a suite of 50 models considered in this study.

We estimate 16 mm/yr on the San Jacinto fault and 3 mm/yr on the Elsinore fault. The Garlock fault is active west of the ECSZ, but accommodates only 0.3–2 mm/yr of left-lateral slip. The White Wolf fault is also active left-laterally at 1.5 mm/yr. Slip rates outside of the ECSZ study area are reported in Table DR1.

IMPLICATIONS FOR SLIP RATE DISCREPANCIES AND CRUSTAL DEFORMATION

Although no individual model reproduces more than five geologic slip rates (Fig. 2A), we may consider the distribution of estimated slip rates on each fault as a proxy for epistemic uncertainty in geodetic slip rates due to fault system geometry, making many of the slip rate discrepancies less absolute (Fig. 3). For example, the 0.5–4.7 mm/yr geodetic rates on the Camp Rock fault overlap with the ≤1.4 ± 0.6 mm/yr geologic rate (Oskin et al., 2008). However, the ranges contain tradeoffs between slip on individual faults, and all models result in ~18 mm/yr of cumulative right-lateral fault slip across the eastern Mojave Desert. In addition, all models estimate 4.4–7.1 mm/yr discrepancies on the Calico fault and 4.1–5.1 mm/yr discrepancies on the Garlock fault (Fig. 3). Persistent discrepancies on specific faults are significant in the context of a methodology that allows for fault system geometries that may be considered analogous to distributed interseismic deformation, i.e., containing up to 56 ECSZ blocks. Distributed deformation (e.g., Bird, 2009; Herbert et al., 2014) therefore does not provide a satisfactory explanation for high geodetic slip rates, or may exist on a wavelength less than the 5–10 km spacing between model faults. Furthermore, a test in which we fix geologic slip rates in the eastern Mojave Desert and estimate a residual homogeneous strain field fits GPS observations with MRV = 1.8 mm/yr (for details, see the Data Repository and Fig. DR5). Misfit differences are small, so although this test does not definitively eliminate the possibility of large amounts of off-fault deformation, it indicates that geodetic observations are more consistent with slip on a subset of ECSZ faults.

While a systematic bias pertains to behavior everywhere within a larger region, persistent discrepancies on individual faults suggest a fault-specific source: either (1) insufficient characterization of geologic slip rates or uncertainties on these faults, or (2) a temporal change in the behavior of these faults. Neither of these possibilities requires an appeal to off-fault deformation processes. Regarding option (1), epistemic uncertainties are commonly not included in geologic slip rate estimates (e.g., Bird, 2007; Gold et al., 2009; Zechar and Frankel, 2009; Behr et al., 2010), potentially leading to unrealistically low reported uncertainties. The presence of near-fault permanent deformation may lead to low geologic slip rates at an individual fault trace (e.g., Shelef and Oskin, 2010; Dolan and Haravitch, 2014); estimated near-fault deformation on the Calico fault (23%; Shelef and Oskin, 2010) does not make up for the 5.8 mm/yr discrepancy.

As for option (2), slip rates in southern California might vary over geologic time (e.g., Dolan et al., 2007). Furthermore, fault behavior in the ECSZ may vary on the time scale of a single earthquake cycle due to postseismic relaxation. In particular, transient deformation following the 1992 M_w 7.3 Landers and 1999 M_w 7.1 Hector Mine earthquakes is likely still present in the 1986–2011 GPS velocity field, even after attempts to remove it (e.g., Liu et al., 2015). The presence of ongoing postseismic relaxation may bias the Calico fault estimate to a higher-than-average interseismic slip rate (e.g., Pollitz et al., 2008; Hearn et al., 2013). Postseismic observations from 2.5 to 10.25 yr following the Hector Mine earthquake suggest up to ~2 mm/yr of transient deformation across the ECSZ (Pollitz, 2015).

CONCLUSION

An algorithmically derived fault geometry containing 10 ECSZ blocks fits GPS observations with an MRV of 1.5 mm/yr, identifies persistent discrepancies between geologically and geodetically estimated slip rates in the eastern California shear zone, and generates a proxy for epistemic uncertainties in geodetic slip rates due to fault system geometry. Assuming 2 mm/yr of transient postseismic deformation, resolving geologic and geodetic slip rates in the eastern Mojave Desert would require ~9 mm/yr of off-fault deformation within <10 km of active faults, which would likely be concentrated around the Calico fault.

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