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A kinematic model for the evolution of the Eastern California Shear Zone and Garlock Fault, Mojave Desert, California

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ABSTRACT

The Eastern California shear zone in the Mojave Desert, California, accommodates nearly a quarter of Pacific–North America plate motion. In south-central Mojave, the shear zone consists of six active faults, with the central Calico fault having the fastest slip rate. However, faults to the east of the Calico fault have larger total offsets. We explain this pattern of slip rate and total offset with a model involving a crustal block (the Mojave Block) that migrates eastward relative to a shear zone at depth whose position and orientation is fixed by the Coachella segment of the San Andreas fault (SAF), southwest of the transpressive "big bend" in the SAF. Both the shear zone and the Garlock fault are assumed to be a direct result of this restraining bend, and consequent strain redistribution. The model explains several aspects of local and regional tectonics, may apply to other transpressive continental plate boundary zones, and may improve seismic hazard estimates in these zones.

1. Introduction

Relative motion between the Pacific and North America plates in the southwestern US is accommodated either by the San Andreas fault in California, or the Eastern California shear zone (ECSZ), sometimes termed the Walker Lane north of the Garlock fault (Sauber et al., 1986, 1994; Dokka and Travis, 1990a,b; Dixon et al., 1995, 2000, 2003; Wesnousky, 2005; Lifton et al., 2013; Thatcher et al., 2016) (Fig. 1). The shear zone formed or accelerated when the southern part of the plate boundary jumped inland to form the modern Gulf of California, resulting in the transpressional "big bend" in the San Andreas fault (Atwater and Stock, 1998; Oskin and Stock, 2003; McQuarrie and Wernicke, 2005). This restraining bend causes high compressional and shear stresses in the adjacent crust, and influences many aspects of regional tectonics. In particular, the shear zone acts as a stress and strain bypass to the restraining bend (e.g., Liu et al., 2010; Plattner et al., 2010). The shear zone is also closely linked to a change in motion of the Sierra Nevada block (north of the Mojave block) in Late Miocene time, from a mainly westward direction relative to stable North America, associated with Basin and Range extension, to its current northwesterly direction (Atwater and Stock, 1998; Wernicke and Snow, 1998). Marine incursion into the northern Gulf of California is dated at 6.2 ± 0.2 Ma (Bennett et al., 2015) and it is likely that the shear zone formed or accelerated around or shortly before this time, i.e., 6–8 Ma (Oskin and Stock, 2003). McQuarrie and Wernicke (2005) place shear zone initiation somewhat earlier, 10–11 Ma. This relative youth, combined with excellent exposures in the arid southwestern US, make the shear zone an important "natural laboratory" for the study of fault evolution and earthquake hazard, especially for complex continental plate boundary zones and restraining bends.

There is an interesting contrast between the expression of the shear zone north and south of the Garlock fault (Fig. 1). North of the Garlock fault, the shear zone consists of three well-defined transtensional fault zones that lie within extensional basins, the westernmost basins of the Basin and Range province. From east to west, these fault zones are the Death Valley–Furnace Creek – Fish Lake Valley fault zone, the Panamint Valley – Hunter Mountain–Saline Valley fault zone, and the Owens Valley–Airport Lake fault zone. South of the Garlock fault, there is little or no extension, no well-developed basins, and more numerous (six) but less mature (lower offset) active strike-slip faults. The Garlock fault reflects the differential extension between the two regions (Davis and Burchfiel, 1973), moving in a left-lateral sense at rate of ∼5–7 mm/yr in its western and central sections, decreasing to the east (e.g., McGill et al., 2009; Ganev et al., 2012; Dolan et al., 2016). Curiously, the ECSZ does not exhibit obvious offset across the Garlock fault, although the Garlock fault is known to be active based on mapped Holocene offsets.

Another curious feature of the ECSZ in the Mojave Desert is a mismatch between the slip rates of the various faults compris-

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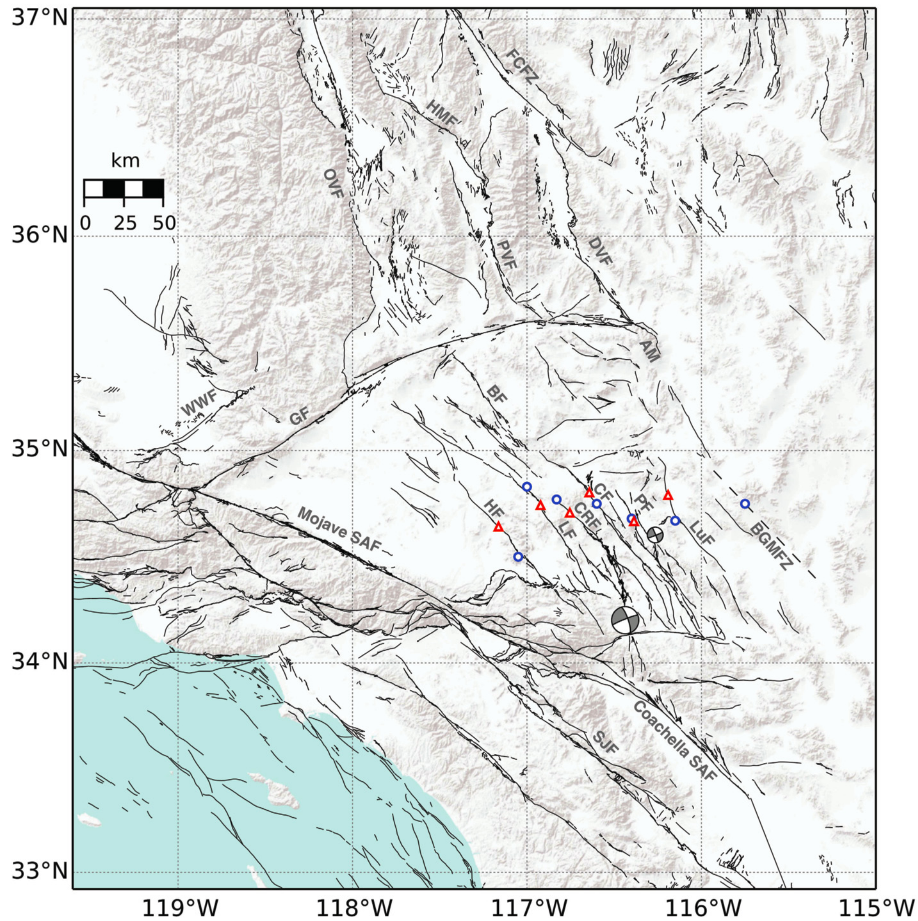

Fig. 1. Fault map of the study area. Red triangles represent locations of late Quaternary fault slip rate estimates (Oskin et al., 2008). Blue circles mark locations of total offset estimates (Miller and Morton, 1980; Dokka, 1983; Glazner et al., 2000; Jachens et al., 2002; Oskin et al., 2007; Lease et al., 2009; Andrew and Walker, 2017). Dashed line represents inferred fault trace of the Bristol–Granite Mountains Fault Zone (Lease et al., 2009). Beach balls mark the 1992 *Mw* 7.3 Landers and 1999 *Mw* 7.1 Hector Mine earthquakes (USGS Earthquake Hazards Program). Fault database from USGS and California Geological Survey. AM is Avawatz Mountains. Fault names are: BGMFZ – Bristol–Granite Mountains fault zone; Blackwater fault; CF – Calico fault; CRF – Camp Rock fault; Coachella SAF – Coachella section of the San Andreas fault; DVF – Death Valley fault; FCFZ – Furnace Creek fault zone; GF – Garlock fault; HF – Helendale fault; HMF – Hunter Mountain fault; LF – Lenwood fault; LuF – Ludlow fault; Mojave SAF – Mojave section of the San Andreas fault; WWF – White Wolf fault; OVF – Owens Valley fault; PVF – Panamint Valley fault; PF – Pisgah fault; SJF – San Jacinto fault. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

ing the shear zone (highest on the central fault, the Calico fault, see Fig. 2a and Oskin et al. (2007, 2008)), and the total displacement on these faults (highest on the easternmost fault, the Bristol–Granite Mountains fault zone; Fig. 2b, Table S1). Dokka and Travis (1990a) suggested that there had a westward shift in the activity of ECSZ faults since their inception. In this paper, we present a simple kinematic model that explains these observations, as well as several other aspects of the regional tectonics.

2. Slip rate and total displacement data

2.1. Slip rate

Oskin et al. (2007, 2008) measured surface displacements and ages on six major dextral faults comprising the ECSZ (Helendale, Lenwood, Camp Rock, Calico, Pisgah, and Ludlow). These data suggest that the central (Calico) fault has the fastest slip rate (Fig. 2a), and the overall summed slip rate for the six faults is $\leq 6.2 \pm 1.9$ mm/yr significantly slower than the cumulative deformation rate across the shear zone derived from geodetic data (e.g., Sauber et al., 1994; Liu et al., 2015). Some authors have explained this difference by off-fault deformation: part of the total slip that occurs during earthquakes is not manifested by on-fault displacement, thus slip rates estimated by geologic methods using offset markers along surface fault traces could miss significant displacement (Shelef and Oskin, 2010; Herbert et al., 2014). Dolan and Haravitch (2014) suggest that off-fault deformation is likely to be more significant for low offset "immature" faults compared to large offset mature faults. Given that all six active faults studied by Oskin et al. (2007, 2008) have total offset <15 km (Fig. 2b), these are immature faults using the criterion of Dolan and Haravitch (2014). Hence, off-fault deformation is likely to be significant.

By studying deformed geologic features at several sites in the Mojave ECSZ, Shelef and Oskin (2010) found that off-fault deformation over zones of 1–2 km width accommodates 0 to ~25% of the total displacement, decreasing away from the fault. In a broader study, Herbert et al. (2014) used a boundary element model to suggest that off-fault deformation accounts for $40\% \pm 23\%$ of the total strain across the ECSZ. If we assume that this latter ratio is representative, and scale the slip rates for all active ECSZ fault (Table S1) then the cumulative deformation rate across the ECSZ is 10.3 ± 5.1 mm/yr (60%, or 6.2 mm/yr, is accommodated by well-defined active faults, and 40%, or 4.1 mm/yr, is accommodated as off-fault deformation and unmapped minor faults). This rate is equivalent within uncertainties to the rate estimated from geodetic data, both for the Mojave section and for the shear zone north of the Garlock fault (Dixon et al., 2000; Miller et al., 2001; Lifton et al., 2013; Xie et al., 2018). Wetmore et al. (2017) and