Transient strain accumulation and fault interaction in the Eastern California shear zone

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INTRODUCTION

Tectonic faults are zones of localized deformation that accommodate plate motion by creeping aseismically at depth and by earthquakes or episodic creep in the upper crust (e.g., Savage and Burford, 1973). It is generally assumed that creep on the deep section of faults and the far-field plate motion remain steady over long time periods, implying a stable rate of stress loading in the elastic part of the crust. This picture seems appropriate to describe the behavior of faults occurring at plate boundaries (Lisowski et al., 1991; Petersen and Wesson, 1994). Within the interior of continental plates, however, the coexistence of faults of various nature, orientation, and direction produces unstable mechanical systems, leading to unsteady kinematics over geological time scales. The time constants involved in processes governing interacting fault systems depend on the geometry of the system, the rates of slip on individual faults, and the amount of distributed strain the crust can accommodate before yielding new faults.

Synthetic aperture radar interferometry (InSAR) data covering the 1992–2000 time period bring new insights into the interseismic surface strain field of the area of the Mojave Desert, California, where the Garlock fault and the Eastern California shear zone intersect. The data reveal, in particular, rates and a spatial distribution of the strain that are inconsistent with long-term fault-slip rates determined from geological data, suggesting unsteady kinematics in the northern Mojave.

ABSTRACT

Satellite synthetic aperture radar interferometry reveals transient strain accumulation along the Blackwater–Little Lake fault system within the Eastern California shear zone. The surface strain map obtained by averaging eight years (1992–2000) of Earth Resource Satellite (ERS) radar data shows a 120-km-long, 20-km-wide zone of concentrated shear between the southern end of the 1872 Owens Valley earthquake surface break and the northern end of the 1992 Landers earthquake surface break. The observed shear zone is continuous through the Garlock fault, which does not show any evidence of left-lateral slip during the same time period. A deformation model of the observed shear indicates right-lateral slip at 7 ± 3 mm/yr on a vertical fault below ~5 km depth, a rate that is two to three times greater than the geologic rates estimated on northwest-trending faults in the eastern Mojave area. This transient slip rate and the absence of resolvable slip on the Garlock fault may be the manifestation of an oscillatory strain pattern between interacting, conjugate fault systems.

Keywords: strain transient, synthetic aperture radar interferometry, Eastern California shear zone.

GEOLOGIC SETTING

The Eastern California shear zone is a 100-km-wide zone of deformation trending approximately N24°W from the eastern end of the compressive fault-bend jog in the San Andreas into the region of east-west extension that bounds the Sierra Nevada block to the east (Dokka and Travis, 1990a, 1990b) (Fig. 1). In the Mojave Desert, the shear zone is formed of several parallel, discontinuous segments bearing evidence of late Cenozoic right-lateral slip. North of the Garlock fault, the shear zone encompasses the Owens Valley Little Lake, the Hunter Mountain Panamint, and the Death Valley fault systems (Fig. 1). Geologic (Dokka and Travis, 1990a) and geodetic (Savage et al., 1990; Sauber et al., 1994; Gan et al., 2000; Miller et al., 2001) data concur to indicate that the shear zone accommodates 6–14 mm/yr of right-lateral slip.
lateral slip, accounting for \( \sim 15\% \) of the North America–Pacific plate relative motion. In 1872, an earthquake of \( M = 7.6 \pm 8 \) ruptured \( \sim 80 \) km of the Owens Valley fault in the northern part of the shear zone (Bea-land and Clark, 1994). Two large earthquakes of \( M > 7 \) produced long surface breaks in the southern section of the shear zone in 1992 and 1999 (Fig. 1).

Although the current shear rate on the Eastern California shear zone is apparently uniform from south to north (Savage et al., 1990), the Quaternary fault traces are not continuous across the Garlock fault (Dokka and Travis, 1990a), a northeast-trending, left-lateral strike-slip fault extending from the western end of the San Andreas fault bend to the southern end of Death Valley (Davis and Burchfiel, 1973) (Fig. 1). Offsets of stream channels, Quaternary deposits, and lake shorelines have been used to determine a long-term slip rate on the fault of 3–11 mm/yr along its western section (Carter, 1980; La Violette et al., 1980) and 4–9 mm along its eastern section (McGill and Sieh, 1993). A geodetic slip rate of \( \sim 11 \) mm/yr has been estimated near its western end (Eberhart-Phillips et al., 1990). Trilateration data suggest that elastic strain decreases toward the east from the central section of the fault (J. Savage, 2000, personal commun.).

**APPROACH**

We processed 25 interferometric pairs of ERS radar images with a perpendicular baseline (separation vector between ERS orbits) smaller than 60 m and time span intervals greater than two years (Fig. 2). To remove residual orbit errors in interferograms, a fine estimation of the baseline of each pair was obtained by nonlinear least-square adjustment of the observed phase to a phase field simulated using a digital elevation map and surface displacement models of the long-term plate motion (Shen et al., 1996) and of the 1992 Landers (Wald and Shearer, 1998) earthquake. Near-surface fault slip is necessary to explain the surface displacement discontinuity observed near Barstow. The data do not resolve any localized shear (within \( \pm 2 \) mm/yr strike slip) along the section of the Garlock fault that intersects the Eastern California shear zone.

**DISCUSSION**

The inferred slip rate on the Blackwater–Little Lake fault system is three times greater than its long-term slip rate estimated from geological data (Dokka and Travis, 1990a; Roquemore, 1988). Conversely, the observed absence of resolvable shear on the eastern section of the Garlock fault indicates that the slip rate on this section of the fault is currently lower than the 10-k.y.-averaged geologic slip rate of \( \sim 7 \) mm/yr (McGill and Sieh, 1993). These observations suggest that the slip velocity on the deep section of a fault, which is assumed to be the long-term slip rate in a steady-state representation, may actually vary over short time scales of 100–10 000 yr when the fault interacts with another fault. In the case discussed here, the Garlock and the Blackwater–Little Lake faults are conjugate, strike-slip faults intersecting one another. The quadruple junction they form is kinematically unstable and may generate an oscillatory surface-velocity pattern in which faults would localize shear strain one at a time.

Episodic strain accumulation in fault zones such as that suggested by InSAR observations along the Blackwater–Little Lake fault system is a plausible explanation of seismic clustering. Recent paleoseismological studies show that the seismic moment release in the southern part of the Eastern California shear zone during the past 10–15 k.y. occurred in clusters at 0–1, 5–6, and 9–10 ka (Rockwell et al., 2001). The sequence of paleoearthquakes on the Garlock fault also indicates

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**Figure 2.** Relative location of Earth Resource Satellite (ERS) orbits at time of data acquisition projected on axis perpendicular to radar line of sight. Perpendicular component of baseline for a given pair is read directly as separation on y-axis. Solid lines connect image pairs analyzed in this study. Orbit numbers are indicated.
irregular return periods (McGill and Rockwell, 1998; Dawson, 2000). Dawson (2000) suggested a correlation between the occurrence of six well-determined events on the Garlock fault and the clusters of seismic activity observed in the southern section of the shear zone. Four of the six Garlock events fall in the most recent cluster; the two other events occurred at 5.1 ka and 6.8 ka—i.e., slightly postdating and pre-dating the penultimate shear zone cluster centered at 5.5 ka. A similar pattern is observed in eastern Turkey, where the sequence of large earthquakes during the past three centuries suggests that the locations and periods of occurrence of seismic moment release alternate between the East Anatolian fault and the North Anatolian fault (Ambraseys, 1973). Using Coulomb stress models, Hubert-Ferrari (1998) interpreted this pattern as the result of the mechanical interaction between the two conjugate fault systems.

Another, nonexclusive way to explain the present rapid shear strain on the Blackwater–Little Lake fault system is to advocate a postseismic process subsequent to the recent large earthquakes in the Eastern California shear zone. The observed shear zone links the southern end of the 1872 Owens Valley surface rupture (Beanland and Clark, 1994) in the north to the northern end of the 1992 Landers surface break in the south (Sieh et al., 1993) (Fig. 1), defining a section of the shear zone that can be viewed as a seismic gap. Coseismic slip and viscoelastic relaxation in the lower crust and upper mantle following these events may have increased the shear stress along the Blackwater–Little Lake fault zone, leading to accelerated fault creep at shallow depth during the past decade. A trend of triggered seismicity was observed after the Landers earthquake from the northern end of the rupture to the southern Owens Valley (Roquemore and Simila, 1994). Furthermore, the sharp displacement gradient observed near the southern end of the imaged section of the shear zone is colocated with the swarm of seismicity that occurred near Barstow after the Landers earthquake (Hauksson et al., 1993; Price and Sandwell, 1998).
CONCLUSIONS

The surface velocity map of the Mojave area obtained by averaging 8 yr of ERS interferometry data reveals that ~50% of the right-lateral motion of the Eastern California shear zone is sharply concentrated along the Blackwater–Little Lake fault system continuously across the Garlock fault. This anomalously fast slip rate and the absence of detectable left-lateral motion along the eastern section of the Garlock fault during the same time period may be the manifestation of an oscillatory strain pattern caused by stress transfer between the two intersecting faults. The absence of Quaternary fault trace across this section of the Garlock fault may indicate that the connection between the Blackwater and the Little Lake faults has never been established in the past; the observed shear would then reveal the birth of a new fault.

The rapid strain accumulation observed along the Blackwater–Little Lake fault system indicates that the fault is currently accumulating stress in the shallow crust at a rate that exceeds the long-term rate inferred from geological data by a factor of about three. Concerns about a potential earthquake on the Calico-Blackwater fault were raised after the 1992 Landers earthquake by the Working Group on the Probabilities of Future Large Earthquakes in Southern California (1992). Should this section of the fault system break in a single event, it would generate an earthquake of magnitude >7 and a surface break exceeding 100 km in length. Such a break would link the gap between the 1872 Owens Valley and 1992 Landers surface ruptures.

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