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

Gilles Peltzer
Fréderic Crampé
Department of Earth and Space Science, University of California, Los Angeles, California 90095, USA, and Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA
Scott Hensley
Paul Rosen
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA

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 dislocation 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.

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 Wesnousky, 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.

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-

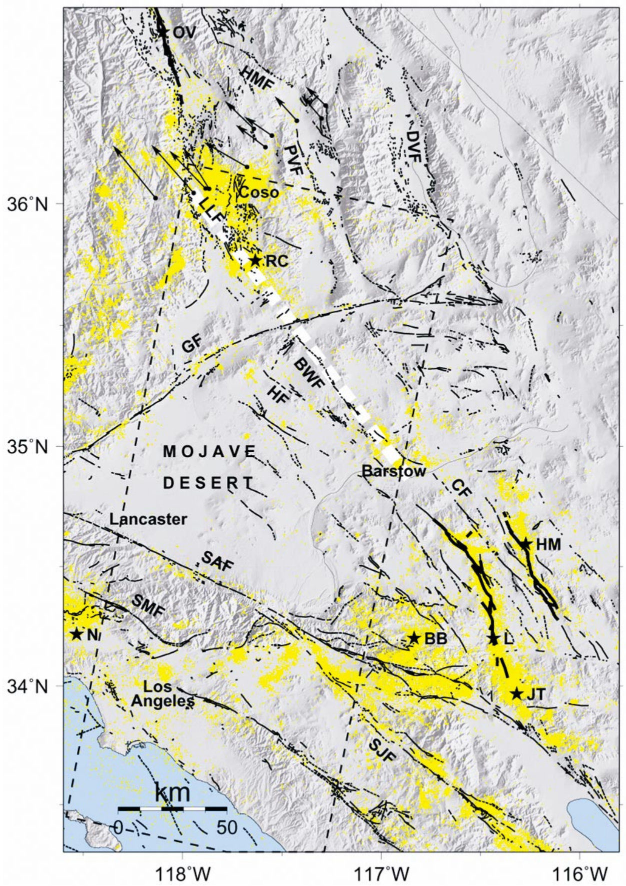

Figure 1. Tectonic map of southern California. Solid lines are active faults (Jennings, 1975). Yellow dots are relocated earthquakes between 1981 and 2000 (Hauksson, 2000). Dashed-line box is area covered by Earth Resource Satellite (ERS) data used in this study. White dashed line shows location of concentrated shear observed in synthetic aperture radar (SAR) data. Black stars indicate epicenters of recent earthquakes: OV—1872 Owens Valley, JT—1992 Joshua Tree, L—1992 Landers, BB—1992 Big Bear, N—1994 Northridge, RC—1994 and 1995 Ridgecrest, HM—1999 Hector Mine. Heavy solid lines depict surface ruptures of Landers (Sieh et al., 1993), Hector Mine (U.S. Geological Survey and California Division of Mines and Geology, 2000; Peltzer et al., 2001), and Owens Valley (Beanland and Clark, 1994; only southern half of rupture is shown) earthquakes. Black dots and arrows show locations and observed velocities of 11 stations of Yucca GPS array (Gan et al., 2000). Faults: SAF—San Andreas, GF—Garlock, BWF—Blackwater, CF—Calico, HMF—Hunter Mountain, PVF—Panamint Valley, DVF—Death Valley, HF—Harper, LLF—Little Lake, SMF—Sierra Madre, SJF—San Jacinto.

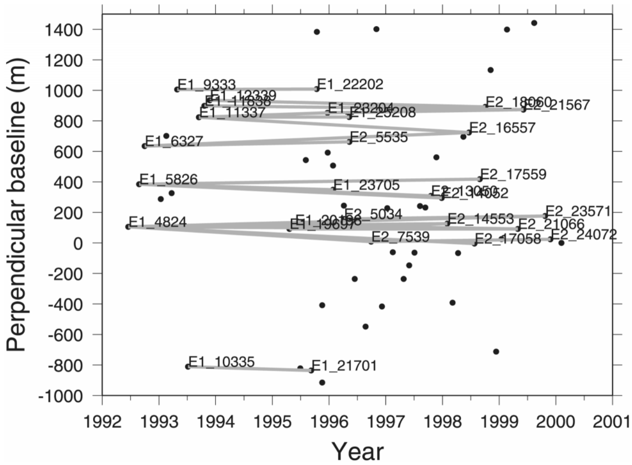

Figure 2. Relative location of Earth Resource Satellite (ERS) orbits at time of data acquisition projected on axis perpendicular to radar line of sight. Perpendicular component of baseline for a given pair is read directly as separation on y-axis. Solid lines connect image pairs analyzed in this study. Orbit numbers are indicated.

lateral slip, accounting for ~15% of the North America–Pacific plate relative motion. In 1872, an earthquake of M 7.6–8 ruptured ~80 km of the Owens Valley fault in the northern part of the shear zone (Beanland 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 ~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 Heaton, 1994), 1994 Northridge (Wald et al., 1996), and 1999 Hector Mine (Peltzer et al., 2001) earthquakes.

The phase propagation delay produced by the water vapor content of the troposphere (Zebker et al., 1997) implies an error of ~5 mm/yr in range-change rate estimates from interferograms spanning ~3 yr. By averaging of 25 interferograms, the residual phase variations were reduced to ~1 mm/yr. Zones of ground subsidence such as observed in urban areas (Los Angeles and Lancaster in Fig. 1) produce a signal that is not modeled in the processing and contribute to the error budget. We used a jackknife procedure (e.g., Rodgers, 1999) to assess the statistical stability of our displacement estimates over smaller areas in the image and obtained a confidence interval of ±0.2 mm/yr. In areas where the spatial variability of the phase residual is low (away from the urban areas), we estimate a total error in range-change rate of ~0.5 mm/yr.

INTERSEISMIC STRAIN IN THE MOJAVE AREA

The velocity map shown in Figure 3 covers a section of the Pacific–North America plate boundary between latitude N33.5° and N36.0°. The gradual color change between the Los Angeles area and the central Mojave block is produced by the right-lateral shear on the San Andreas fault and is consistent with displacement velocities observed at geodetic stations in the Los Angeles area (Peltzer et al., 1998). From ~30 km north of the San Andreas fault up to the Blackwater fault, the line-of-sight displacement gradient is relatively uniform and equals $\sim 2.5 \times 10^{-2}$ mm·yr^{-1}·km^{-1} perpendicular to the San Andreas fault, in agreement with crustal velocity models of southern California (Shen et al., 1996). More important, the map shows a zone, trending N36°W, of localized shear parallel to the Blackwater–Little Lake fault system extending from the eastern edge of the SAR frame near the city of Barstow across the Garlock fault and into the Coso volcanic field (Figs. 1, 3). The cross-section view of the SAR data (Fig. 4) shows that the shear zone is concentrated within ~10 km on either side of the Blackwater fault, producing a step of 1.2 ± 0.5 mm/yr in the range velocity field. The shear zone becomes narrower as it approaches the southern end of the imaged area. At the latitude of Barstow, the line-of-sight velocity field bears a discontinuity of ~1.5 mm/yr. The observed shear is consistent with the distribution, direction, and magnitude of right-lateral shear observed with the Global Positioning System (GPS) north of the imaged area (Gan et al., 2000) (Figs. 1, 4). Elastic half-space dislocation modeling (Okada, 1985) indicates that the observed shear strain can be explained by right-lateral slip at a rate of 7 ± 3 mm/yr on a vertical plane parallel to the Blackwater–Little Lake fault system and locked above the depth of 5 km (Fig. 4). Such a shallow locking depth is consistent with the maximum depth of seismicity of 5–7 km in this part of the Mojave between 1975 and 1998 (Richards-Dinger and Shearer, 2000). Near-surface fault slip is necessary to explain the surface displacement discontinuity observed near Barstow. The data do not resolve any localized shear (within ±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 ~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

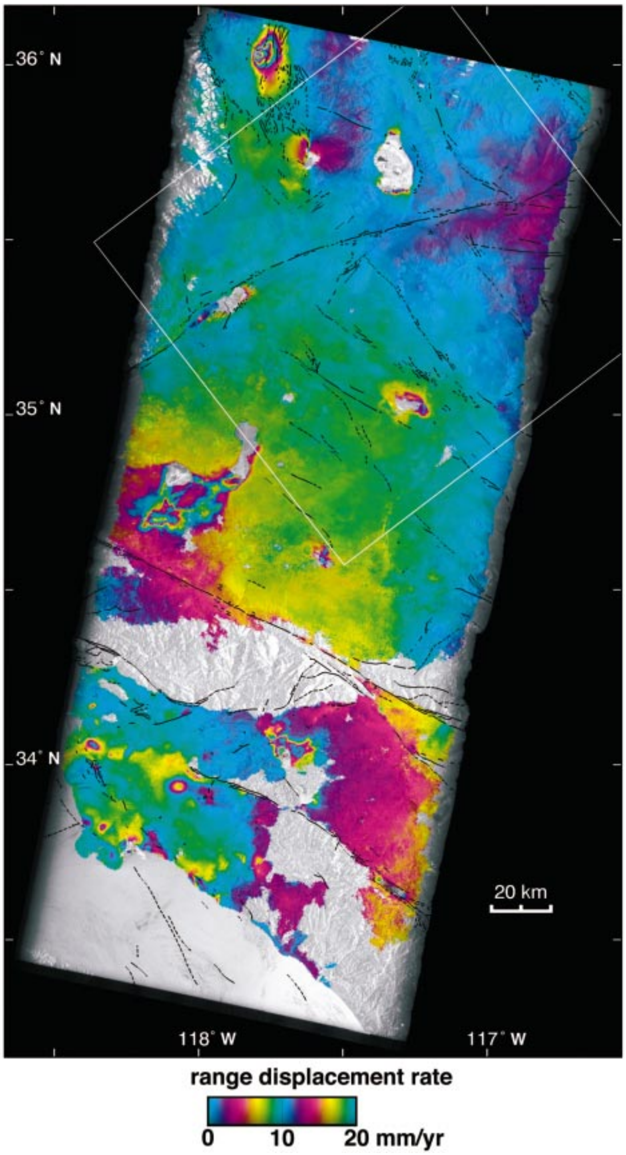

Figure 3. Surface velocity map obtained by averaging 25 interferograms of Los Angeles–Mojave region. One color cycle depicts 10 mm/yr of surface displacement along radar line of sight (at lat N34°; ERS [Earth Resource Satellite] descending track trends S13.6°W, radar looking westward at 23° off vertical incidence angle in middle of imaged swath). Gray areas are zones of low phase coherence that have been masked in processing. Black lines are active faults (Jennings, 1975). White box indicates subset of synthetic aperture radar (SAR) data that was used for profile in Figure 4. Note conspicuous shear strain along San Andreas fault and shear zone parallel to Blackwater–Little Lake fault system. Large deformation signal in northwest corner of frame is ground subsidence related to Coso volcanic and geothermal field (Fig. 1). Surface displacement associated with 1994 and 1995 Ridgecrest earthquakes is visible south of Coso area. Other patterns of surface deformation include ground subsidence due to groundwater withdrawal in Los Angeles and Lancaster areas (Fig. 1) and to seasonal change of water table level around dry lakes.

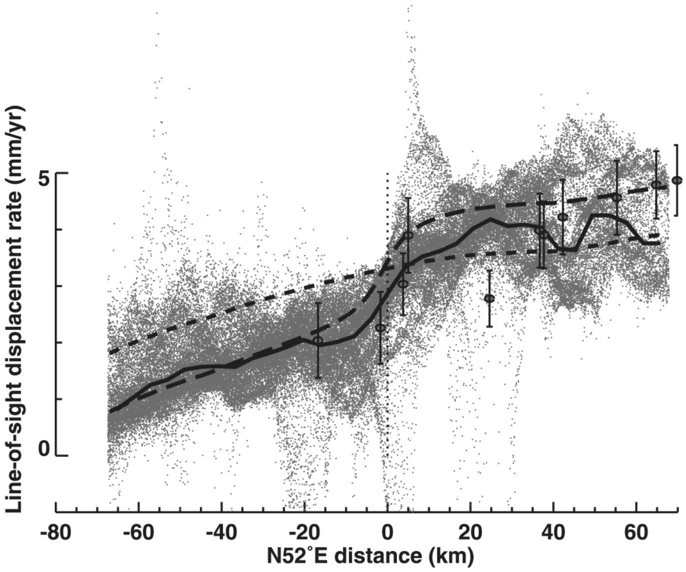

Figure 4. Profiles of observed and modeled line-of-sight displacement projected on vertical plane perpendicular to shear zone. Gray dots are individual data points for all radar-image pixels included in box shown in Figure 3. Solid line shows 2 km running mean of observed displacement along profile length. Note that apparent standard deviation of projected data relative to average profile reflects in part displacement gradient parallel to fault strike and not only error in data. Groups of dots that deviate from dense part of profile are due to ground subsidence near lake shores and to surface displacement associated with Ridgecrest earthquakes (Figs. 1, 3). Short-dash line is profile predicted by long-term velocity model used to estimate interferometric baseline (Shen et al., 1996). Long-dash line is profile predicted by velocity model, including additional buried dislocation along Blackwater–Little Lake fault system. Parameters of added fault are given in text. Black dots and error bars (2σ) are line-of-sight projections of horizontal velocities observed by GPS at stations of Yucca transect (Gan et al., 2000).

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.

ACKNOWLEDGMENTS

We thank P. Tapponnier, K. Sieh, and J. Savage for discussions; T. Dawson for providing a copy of his M.S. thesis before publication; Z.K. Shen for providing his velocity model of southern California, and W. Thatcher and R. Dokka for reviewing the manuscript. ERS data were provided by the European Space Agency. The work was performed in part at the Jet Propulsion Laboratory under contract with the National Aeronautics and Space Administration.

REFERENCES CITED

Ambraseys, N.N., 1973, Value of historical record of earthquakes: Nature, v. 232, p. 375–379.

Beanland, S., and Clark, M.M., 1994, The Owens Valley fault zone, eastern California, and surface faulting associated with the 1872 earthquake: U.S. Geological Survey Bulletin 1982, 29 p.

Carter, B.A., 1980, Quaternary displacement on the Garlock fault, California, *in* Fife, D.L., and Brown, A.R., eds., Geology and mineral wealth of the California desert: Santa Ana, California, South Coast Geological Society, p. 457–466.

Davis, G.A., and Burchfiel, B.C., 1973, Garlock fault: An intracontinental transform structure, southern California: Geological Society of America Bulletin, v. 84, p. 1407–1422.

Dawson, T.H., 2000, A 7000 years record of paleoearthquakes on the central Garlock fault, near El Paso Peaks, California [M.S. thesis]: San Diego, California, San Diego State University, 87 p.

Dokka, R.K., and Travis, C.J., 1990a, Late Cenozoic strike-slip faulting in the Mojave desert, California: Tectonics, v. 9, p. 311–340.

Dokka, R.K., and Travis, C.J., 1990b, The role of the Eastern California shear zone in accommodating Pacific–North America plate motion: Geophysical Research Letters, v. 17, p. 1323–1326.

Eberhart-Phillips, D., Lisowski, M., and Zoback, M.D., 1990, Crustal strain near the big bend of the San Andreas fault: Analysis of the Los Padres–Tehachapi trilateration networks: Journal of Geophysical Research, v. 95, p. 1139–1153.

Gan, W., Svarc, J.L., Savage, J.C., and Prescott, W.H., 2000, Strain accumulation across the Eastern California shear zone at latitude 36°30′N: Journal of Geophysical Research, v. 105, p. 16 229–16 236.

Hauksson, E., 2000, Crustal structure and seismicity distribution adjacent to the Pacific and North America plate boundary in southern California: Journal of Geophysical Research, v. 105, p. 13 875–13 903.

Hauksson, E., Jones, L.M., Hutton, K., and Eberhart-Phillips, D., 1993, The 1992 Landers earthquake sequence: Seismological observations: Journal of Geophysical Research, v. 98, p. 19 835–19 858.

Hubert-Ferrari, A., 1998, La faille Nord Anatolienne, cinématique, morphologie, localization, vitesse et modélisation utilisant la contrainte de Coulomb [Ph.D. Thesis]: Paris, University of Paris VII.

Jennings, C.W., 1975, Fault map of California: Sacramento, California Department of Conservation, California Geologic Data Map No. 1, scale 1:750 000.

La Violette, J.W., Christenson, G.E., and Stepp, J.C., 1980, Quaternary displacement of the western Garlock fault, southern California, *in* Fife, D.L., and Brown, A.R., eds., Geology and mineral wealth of the California desert: Santa Ana, California South Coast Geological Society, p. 449–456.

Lisowski, M., Savage, J.C., and Prescott, W.H., 1991, The velocity field along the San Andreas fault: Journal of Geophysical Research, v. 96, p. 8369–8389.

McGill, S.F., and Rockwell, T., 1998, Ages of late Holocene earthquakes on the central Garlock fault near El Paso Peaks: Journal of Geophysical Research, v. 103, p. 7265–7279.

McGill, S.F., and Sieh, K., 1993, Holocene slip-rate of the central Garlock fault in southeastern Searles Valley: Journal of Geophysical Research, v. 98, p. 14 217–14 231.

Miller, M.M., Johnson, D.J., Dixon, T.H., and Dokka, R.K., 2001, Refined kinematics of the Eastern California shear zone from GPS observations, 1993–1998: Journal of Geophysical Research, v. 106, p. 2245–2263.

Okada, Y., 1985, Surface deformation due to shear and tensile faults in a half-space: Geological Society of America Bulletin, v. 75, p. 1135–1154.

Peltzer, G., Crampé, F., and Hensley, S., 1998, Elastic strain accumulation along the Mojave section of the San Andreas fault, California, observed with InSAR: Eos (Transactions, American Geophysical Union), v. 79, p. 33.

Peltzer, G., Crampé, F., and Rosen, P., 2001, The Mw 7.1 Hector Mine, California earthquake, surface rupture, surface displacement field and fault slip solution from ERS SAR data: Academie des Sciences, Paris, Comptes Rendus (in press).

Petersen, M.D., and Wesnousky, S.G., 1994, Fault slip rates and earthquake histories for active faults in Southern California: Seismological Society of America Bulletin, v. 84, p. 1608–1649.

Price, E.J., and Sandwell, D., 1998, Small scale deformations associated with the 1992 Landers, California, earthquake mapped by synthetic radar interferometry: Journal of Geophysical Research, v. 103, p. 27 001–27 016.

Richards-Dinger, K.B., and Shearer, P.M., 2000, Earthquake locations in Southern California obtained using source specific station terms: Journal of Geophysical Research, v. 105, p. 10 939–10 960.

Rockwell, T.K., Lindvall, S., Herzberg, M., Murbach, D., Dawson, T., Berger, G., and Huntley, D.J., 2001, Paleoseismology in the Johnson Valley, Kickapoo, and Homestead Valley faults of the Eastern California shear zone: Geological Society of America Bulletin, v. 90, p. 1200–1236.

Rodgers, J.L., 1999, The bootstrap, the jackknife, and the randomization test: A sampling taxonomy: Multivariate Behavioral Research, v. 34, p. 441–456.

Roquemore, G.R., 1988, Revised estimates of the slip rate on the Little Lake fault, California: Geological Society of America Abstracts with Programs, v. 20, no. 3, p. 225.

Roquemore, G.R., and Simila, G.W., 1994, Aftershocks from the June 1992 Landers earthquake: Northern Mojave Desert to the Coso volcanic field: Geological Society of America Bulletin, v. 84, p. 854–862.

Sauber, J., Thatcher, W., Solomon, S.C., and Lisowsky, M., 1994, Geodetic slip rate for the Eastern California shear zone and the recurrence time of Mojave desert earthquakes: Nature, v. 367, p. 264–266.

Savage, J.C., and Burford, B.O., 1973, Geodetic determination of relative plate motion in central California: Journal of Geophysical Research, v. 78, p. 832–845.

Savage, J.C., Lisowsky, M., and Prescott, W.H., 1990, An apparent shear zone trending north-northwest across the Mojave Desert into Owens Valley, eastern California: Geophysical Research Letters, v. 12, p. 2113–2116.

Shen, Z.K., Jackson, D.D., and Ge, B.X., 1996, Crustal deformation across and beyond the Los Angeles basin from geodetic measurements: Journal of Geophysical Research, v. 101, p. 27 957–27 980.

Sieh, K., Jones, L.M., Hauksson, E., Hudnut, K.W., Eberhart-Phillips, D., Heaton, T.H., Hough, S.E., Hutton, L.K., Kanamori, H., Lilje, A., Lindvall, S.C., McGill, S.F., Mori, J.J., Rubin, C.M., Spotila, J.A., Stock, J.M., Thio, H.K., Treiman, J.A., Wernicke, B.P., and Zachariasen, J., 1993, Near-field investigations of the Landers earthquake sequence, April to July, 1992: Science, v. 260, p. 171–176.

U.S. Geological Survey and California Division of Mines and Geology, 2000, Preliminary report on the 10/16/1999 M 7.1 Hector Mine, California earthquake: Seismological Research Letters, v. 71, p. 11.

Wald, D.J., and Heaton, T.H., 1994, Spatial and temporal distribution of slip for the 1992 Landers, California earthquake: Seismological Society of America Bulletin, v. 84, p. 668–691.

Wald, D.J., Heaton, T.H., and Hudnut, K., 1996, The slip history of the 1994 Northridge, California earthquake determined from strong-motions, teleseismic, GPS, and levelling data: Seismological Society of America Bulletin, v. 86, p. 49–70.

Working Group on the Probabilities of Future Large Earthquakes in Southern California, 1992, Future seismic hazards in Southern California: U.S. Geological Survey California and California Division of Mines and Geology, 42 p.

Zebker, H.A., Rosen, P., and Hensley, S., 1997, Atmospheric effects in interferometric synthetic aperture radar surface deformation and topographic maps: Journal of Geophysical Research, v. 102, p. 7547–7563.

Manuscript received January 3, 2001
Revised manuscript received June 20, 2001
Manuscript accepted July 9, 2001

Printed in USA