

ROLE OF THE EASTERN CALIFORNIA SHEAR ZONE IN ACCOMMODATING PACIFIC-NORTH AMERICAN PLATE MOTION

Roy K. Dokka and Christopher J. Travis

Department of Geology and Geophysics, Louisiana State University, Baton Rouge

Abstract. The newly recognized Eastern California shear zone (ECSZ) of the Mojave Desert-Death Valley region has played a major, but previously underappreciated role in accommodating the dextral shear between the Pacific and North American plates in late Cenozoic time. Comparison of integrated net slip along the shear zone with motion values across the entire transform boundary indicates that between 9% and 23% of the total relative plate motion has occurred along the ECSZ since its probable inception ~10-6 Ma. Long-term integrated shear along the ECSZ ($6.7 \pm 1.3 \text{ mm yr}^{-1}$) is similar to historic measurements ($6.7 \pm 1.3 \text{ mm yr}^{-1}$). Time-space patterns of faulting suggest that shear was concentrated in the eastern part of the Mojave Desert block and Death Valley during late Miocene and early Pleistocene time, but that the locus of faulting in the south-central Mojave jumped westward between 1.5 and 0.7 Ma.

INTRODUCTION

Plate tectonic theory has given geologists the means with which to understand the kinematic history of and strain rates along plate boundaries such as the Pacific-North American transform. The pioneering work of Tanya Atwater [1970] put the San Andreas fault system as well as other late Cenozoic tectonic elements of western North America into a global tectonic perspective for the first time. Her classic analysis and the more detailed reconstructions that have followed have provided geologists with both a regional tectonic framework for their observations and a quantitative upper limit on integrated shear across this broad transform zone [e.g., Minster et al., 1974; Minster and Jordan, 1978, 1987; DeMets et al., 1987; Stock and Molnar, 1988]. Recent plate circuit reconstructions predict that ~1360 km of right slip has occurred along this boundary since its inception near 35 Ma [Stock and Molnar, 1988]. The challenge to geologists is to determine how and where this strain is partitioned.

Much progress has been made in recent years in understanding present-day regional and local shear strains and slip rates of the plate boundary in central and southern California [e.g., Prescott et al., 1979; Sieh and Jahns, 1984; Weldon and Sieh, 1985; Lyzenga et al., 1986; Sauber et al., 1986]. Several useful kinematic models have also been advanced to explain recent motions based on Quaternary slip and present-day strain rate data [Minster and Jordan, 1978, 1987; Bird and Rosenstock, 1984; Wesnousky, 1986; Weldon and Humphreys, 1986; Humphreys and Weldon, 1990]. Our understanding of the long-term behavior of the boundary is less certain, however, owing to the lack of detailed information on the movement histories of many of the faults of the region and the inherent uncertainties associated with relating short-term strain data to long-term effects. In this paper we address the questions of how much of Pacific-North American plate motion may have been accommodated on faults of the Mojave Desert-Death Valley region, how the locus of strain may have shifted with time within this region, and how strain rates may have varied through time.

THE EASTERN CALIFORNIA SHEAR ZONE

Most syntheses dealing with the evolution of the Pacific-North American transform boundary have emphasized the part played by the San Andreas fault system and subparallel faults to the west (Figure 1), even though the existence of similar late Cenozoic faults in the Mojave Desert and east of the Sierra Nevada has been well established [e.g., Longwell, 1960; Dibblee, 1961; Burchfiel and Stewart, 1966; Hamilton and Myers, 1966; Hill and Troxel, 1966]. Recent studies by the authors were initiated to better understand the kinematic development of NW-striking right slip faults of the Mojave Desert Block and their role in the tectonic framework of southern California. Previously, most tectonic models for southern California have treated the entire Mojave Desert Block as the site of distributed simple shear (i.e., homogeneous strain) during post-middle Miocene time [Garfunkel, 1974; Carter et al., 1987]. In contrast, our analysis of the region indicates that strain is regionally heterogeneous and is partitioned into six domains that are separated by major strike-slip faults and extensional zones [Dokka and Travis, 1990]. Tectonic rotation of these domains as well as their internal deformation by strike-slip faulting have occurred as the result of broadly distributed regional right shear; sixty-five km of total right slip is reckoned to have occurred along faults of the southern half of the province. This broad network of faults, along with kinematically and temporally similar strike-slip faults of the Death Valley region (Furnace Creek and Southern Death Valley fault zones), constitute a regional, throughgoing zone of right shear named by Dokka and Travis [1990], the *Eastern California shear zone* (ECSZ). This zone of intracontinental shear likely continues to the north where it may include the Walker Lane belt of western Nevada (Figure 1).

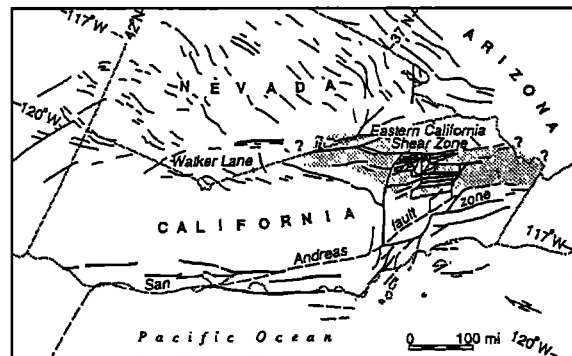


Fig. 1. The Pacific-North American transform boundary in the western USA highlighting the location of the Eastern California shear zone.

Regional and local dated cross-cutting relations constrain the time of onset of right shear across the ECSZ. At the regional scale, all late Cenozoic strike-slip faults of the central and eastern Mojave cut and fully displace ~20 Ma elements of the early Miocene Mojave Extensional Belt [Dokka, 1983, 1989ab]. Locally, the best evidence for the age of initiation of an individual fault in the central Mojave can be seen in the Calico Mountains-Mud Hills area along the Calico-Blackwater fault [Dokka, 1989a]. Here, the youngest dated rock that is

displaced the full amount (10 km) is a 13.4 ± 0.2 Ma tuff from near the top of the Barstow Formation [MacFadden et al., 1990]. The Garlock fault (northern boundary of the Mojave Desert Block) was initiated near 10 Ma [Burbank and Whistler, 1987] and is truncated at its extreme eastern end by faults of the ECSZ (southern Death Valley fault zone [Davis and Burchfiel, 1973; Plescia and Henyey, 1982]). Age relations described by Stewart [1983] in the adjacent Death Valley region imply that faulting in that part of the ECSZ may have begun as recently as late Miocene (~6 Ma). Paleomagnetic data from rocks south of the Pinto Mountain fault in the adjacent eastern Transverse Ranges suggest that regional deformation there and, by inference, deformation of the Mojave Desert Block began after ~10 Ma [Carter et al., 1987]. Based on the data presented above, we conclude that the ECSZ became active no earlier than 20 Ma and no later than 6 Ma. An initiation time between ~10 Ma and 6 Ma (late Miocene) is considered to be most likely.

Tectonic patterns from the southern Mojave portion of the ECSZ indicate that the locus of faulting and deformation in this broad, regional zone has not remained fixed, but has apparently shifted westward with time. For example, although the Granite Mountains and Bristol Mountains faults of the eastern portion of the province accommodated >54% of the regional right shear in the Mojave Desert Block (Figure 2), these faults, as well as the small Broadwell Lake fault are apparently not active today judging by the paucity of earthquakes and by the lack of ground ruptures or geomorphic features indicative of recent surface movements [Dokka and Travis, 1990]. These faults may have become inactive only quite recently (<1 Ma?), however, judging by the occurrence of probable late Quaternary gravels that overlie the Granite Mountains fault [Davis, 1977], Bristol Mountains fault [Brady et al., 1988], and Broadwell Lake fault [Ford et al., 1990]. These gravels are partially lithified fluvial and alluvial fan debris that occur in deposits that are undergoing dissection by presently active streams.

Localization of shear in the eastern Mojave during earlier times is in marked contrast with the present pattern of strain, where the distribution of earthquakes (C. Jones, cited in Dokka and Travis [1990]), distortion of the Mojave regional strain net [Sauber et al., 1986], and recent ground rupture [Morton et al., 1980; Dokka, 1983; Hill and Beeby, 1977] indicate that regional shear in the area south of latitude 35°N is now concentrated between the Helendale and Ludlow faults. In further contrast to the inactive faults of the southeastern Mojave, presently active faults of the south-central Mojave (Helendale, Lenwood, and Camp Rock faults) display small individual and cumulative net slips (7 km; Dokka [1983]). If the present shear rate of $6.7 \pm 1.3 \text{ mm yr}^{-1}$ [Sauber et al., 1986] across the south-central Mojave has prevailed during the recent past, then all of the observed fault slips in the region can be accounted for in the last ~1 m.y. (since middle Pleistocene). This timing inference is supported by relationships from the northern San Bernardino Mountains which suggest that shears belonging to the currently active family of NW-striking right-slip faults of the Mojave Desert Block were initiated between 1.5 and 0.7 Ma [Meisling and Weldon, 1989]. Although we recognize that data from the south-central Mojave Desert (Helendale, Lenwood, and Camp Rock faults) and the San Bernardino Mountains area [R. E. Weldon, 1990, written communication] do not preclude pre-middle Pleistocene strike-slip fault movements, we contend that if such movement occurred it was small (<1 km).

Coupling the faulting inception constraints presented above (~10–6 Ma) with the total net slip across the ECSZ at the latitude of the Mojave Desert Block (65 km), the integrated slip rate is $6\text{--}12 \text{ mm yr}^{-1}$ (Table 1). This long term rate is similar to the present shear rate of $6.7 \pm 1.3 \text{ mm yr}^{-1}$ determined from geodetic measurements made over the past ~40 years from the south-central Mojave [Sauber et al., 1986]. Long-term data presented here suggest that shear may have been nearly

constant since late Miocene inception, even though the locus of faulting in the southern Mojave portion of the ECSZ has apparently shifted recently to the west.

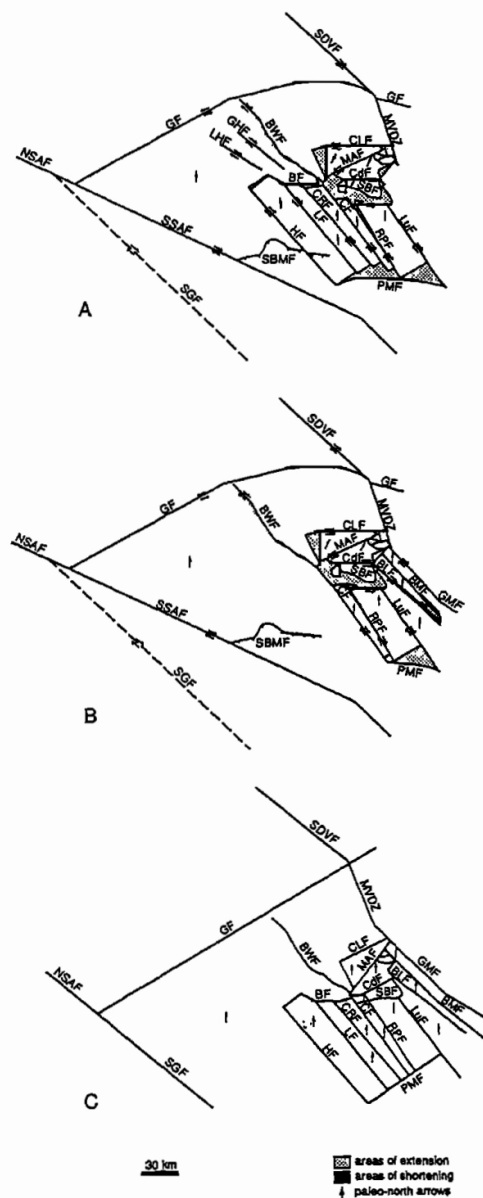


Fig. 2. Kinematic model of Dokka and Travis [1990] showing development of the Eastern California shear zone. (A) Present-day. (B) ca. 1 Ma. (C) Pre-faulting, ca. 10 Ma. BF, Barstow fault; BWF, Blackwater fault; BMF, Bristol Mountains fault; BLF, Broadwell Lake fault; CdF, Cady fault; CF, Calico fault; CRF, Camp Rock fault; CLF, Coyote Lake fault; GF, Garlock fault; GMF, Granite Mountains fault; GHF, Gravel Hills fault; HF, Helendale fault; LF, Lenwood fault; LHF, Lockhart fault; LuF, Ludlow fault; MF, Manix fault; MVDZ, Mesquite Valley disturbed zone; PMF, Pinto Mountain fault; RPF, Rodman-Pisgah fault; SBF, Sleeping Beauty fault; NSAF, northern San Andreas fault; SSF, San Gabriel fault; SSABF, southern San Andreas fault; SDVF, southern Death Valley fault zone; SBMF, San Bernardino Mountains fault. Internal structure of NE Mojave not shown.

THE EASTERN CALIFORNIA SHEAR ZONE AND THE PACIFIC-NORTH AMERICAN TRANSFORM

In order to establish that late Cenozoic faults of the Eastern California shear zone are part of the Pacific-North American

TABLE 1. Pacific-North American transform displacement accommodated by the Eastern California shear zone.

Time Interval (m.y.)	Pacific-North American displacement (km) ^a	Partitioned on ECSZ (%) ^b	Slip rate (mm/yr) ^c
5.5	325±45	18-23	12
10.59	635±70	9-12	6
19.90	875±70	7-8	3

^a Displacements calculated for a point on the Pacific plate presently located near the Mendocino Triple Junction [Stock and Molnar, 1988].

^b Total right slip along Eastern California shear zone at 35°N latitude is 65 km [Dokka and Travis, 1990]. Additional (<15 km) shear displacement may have occurred east between the Granite Mountains fault and the California state line judging by young (?), linear valleys and mountain fronts.

^c Speed calculated using net slip constraints on the Eastern California shear zone and the time elapsed since fault initiation.

plate boundary, physical as well as kinematic linkage between the ECSZ and the San Andreas fault system must be demonstrated. Dokka and Travis [1990] have shown that an unbroken path of ~10-0 Ma strike-slip faults and connecting extensional basins can be traced from the Death Valley area through to the southern Mojave Desert. The physical as well as kinematic connection with San Andreas structures can be most easily demonstrated by tracing currently active faults of the ECSZ into the San Andreas system in the vicinity of the Pinto Mountain fault. Here, seismogenic faults of the south-central Mojave (Emerson strand of the Camp Rock fault, Mesquite Lake strand of the Calico fault, and unnamed strands of the Lenwood and Rodman-Pisgah faults) terminate against the currently active, east-striking Pinto Mountain fault, which in turn ends to the west against the active San Andreas north branch fault [Dibblee, 1975] (Figure 3). The notion of kinematic linkage of these structural systems is further supported by the regional fault slip budget. Humphreys and Weldon [1990] have assembled recent fault slip rates on the San Andreas fault and its splays throughout southern California and conclude that the total rate is ~40 mm/yr. They reckon that the San Jacinto fault splays from the San Andreas in the Transverse Ranges and accounts for 8-14 mm/yr of the shear in southernmost California; the remainder is accommodated by the San Andreas fault. The slip rate on the San Andreas fault just southeast of Cajon Pass is 24±4 mm/yr, but increases to 29±6 mm/yr near the northern Salton Trough [Humphreys and Weldon, 1990]. This discrepancy is accounted for by motion along the presently active right-slip faults of the south-central Mojave (Figure 4; Humphreys and Weldon [1990]). Data presented above support Humphreys' and Weldon's contention that kinematic linkage presently exists between the San Andreas system and the Eastern California shear zone. These relations also suggest that such a linkage has existed since late Miocene time.

The kinematic history of the ECSZ has important implications for models of southern California. Firstly, relations described here confirm the long-standing notion, first advanced by Atwater [1970], that a significant amount of Pacific-North American transform shear has been accommodated by structures that lie well east of the San Andreas fault. Secondly, the long-term slip history data of the ECSZ allows quantitative assessment of its role in the development of the Pacific-North American plate boundary.

The role played by the ECSZ in accommodating Pacific-North American transform motion can be put into perspective

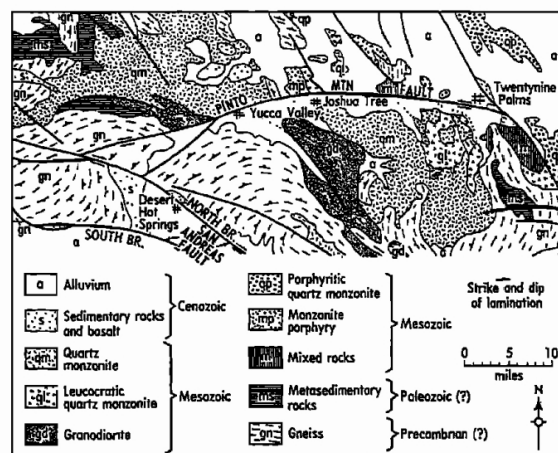


Fig. 3. General geologic map showing relationship of faults of the Eastern California shear zone with the Pinto Mountain fault and the San Andreas fault system (after Dibblee [1975]).

by comparing their respective slip histories. We have used values presented in Stock and Molnar [1988] of total relative displacement between the Pacific and North American plates and uncertainties for magnetic anomaly intervals 0-3 (0-5.5 Ma), 0-5 (0-10.59 Ma), and 0-6 (0-19.90 Ma) as the basis for our comparison with the integrated right slip along the ECSZ (Table 1). These time intervals were chosen because they most closely correspond to the timing constraints discussed above on the age of initiation of faulting along the ECSZ.

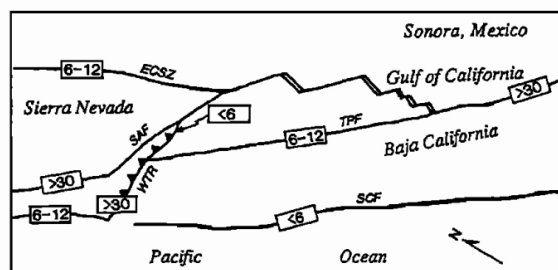


Fig. 4. Schematic map illustrating present-day kinematics of southern California and environs (modified after Humphreys and Weldon [1990]). Values shown are fault slip rates in mm yr⁻¹. ECSZ, Eastern California shear zone; SAF, San Andreas fault; SCF, San Clemente fault; TPF, transpeninsular faults; WTR, western Transverse Ranges.

It is clear from this comparison that the ECSZ has played a major role in accommodating late Cenozoic motion between the Pacific and North American plates. Given initiation times of 19.90 Ma, 10.59 Ma, or 5.5 Ma, the ECSZ has accommodated 7-8%, 9-12%, or 18-23% of the total plate motion, respectively. Because initiation is considered here to have most likely occurred between 10 and 6 Ma, 9% to 23% of the total relative motion between the Pacific and North American plates has been accommodated by the ECSZ.

Acknowledgements. We thank R. E. Weldon and an anonymous referee for their reviews. Discussions with W. Hamilton, G. A. Davis, R. Brady, B. Luyendyk, J. Ford, R. Blom, T. Ross, and M. Woodburne were helpful. Supported by the National Science Foundation (EAR-8107524, EAR-8407136, EAR-8721022, and EAR-9004339).

REFERENCES

Atwater, T., Implications of plate tectonics for the Cenozoic

- tectonic evolution of western North America, *Geol. Soc. Am. Bull.*, 81, 3513-3536, 1970.
- Bird, P., and R. W. Rosenstock, Kinematics of present crust and mantle flow in southern California, *Geol. Soc. Am. Bull.*, 95, 946-957, 1984.
- Brady, R. H., III, J. Clayton, B. W. Troxel, K. L. Verosub, A. Cregan, and M. Abrams, Thematic Mapper and field investigations at the intersection of the Death Valley and Garlock fault zones California, *Remote Sens. Environ.*, 28, 207-217, 1988.
- Burbank, D. W., and D. P. Whistler, Temporally constrained tectonic rotations derived from magnetostratigraphic data: Implications for the initiation of the Garlock fault, California, *Geology*, 15, 1172-1175, 1987.
- Burchfiel, B. C., and J. H. Stewart, "Pull-apart" origin of the central segment of Death Valley, California, *Geol. Soc. Am. Bull.*, 77, 439-442, 1966.
- Carter, J. N., B. P. Luyendyk, and R. R. Terres, Neogene clockwise rotation of the eastern Transverse Ranges, California, suggested by paleomagnetic vectors, *Geol. Soc. Am. Bull.*, 98, 199-206, 1987.
- Davis, G. A., Limitations on displacement and southeastward extent of the Death Valley fault zone, California, *Calif. Geology*, 30, 27-33, 1977.
- Davis, G. A., and B. C. Burchfiel, Garlock fault, an intracontinental transform structure, southern California, *Geol. Soc. Am. Bull.*, 84, 1407-1422, 1973.
- DeMets, C., R. G. Gordon, S. Stein, and D. F. Argus, A revised estimate of Pacific-North American plate motion and implications for western North American plate boundary zone tectonics, *Geophys. Res. Lett.*, 14, 911-914, 1987.
- Dibblee, T. W., Jr., Evidence of strike-slip faulting along northwest-trending faults in the Mojave Desert, *U.S. Geol. Surv. Prof. Pap.* 424-B, B197-B199, 1961.
- Dibblee, T. W., Jr., Late Quaternary uplift of the San Bernardino Mountains on the San Andreas and related faults, in San Andreas fault in southern California, edited by J. C. Crowell, pp. 127-135, Calif. Div. Mines and Geol. Sp. Rept. 118, 1975.
- Dokka, R. K., Displacements on late Cenozoic strike-slip faults of the central Mojave Desert, California, *Geology*, 11, 305-308, 1983.
- Dokka, R. K., The Mojave Extensional Belt of southern California, *Tectonics*, 8, 363-390, 1989a.
- Dokka, R. K., Correction to "The Mojave Extensional Belt of southern California", *Tectonics*, 8, 937, 1989b.
- Dokka, R. K., and C. J. Travis, Late Cenozoic strike-slip faulting in the Mojave Desert, California, *Tectonics*, 9, 311-340, 1990.
- Ford, J. P., R. K. Dokka, R. E. Crippen, and R. G. Blom, Recognition of previously unknown faults revealed by enhanced Landsat TM images in the Mojave Desert, California, *Science*, (in press), 1990.
- Garfunkel, Z., Model for the late Cenozoic tectonic history of the Mojave Desert and its relation to adjacent areas, *Geol. Soc. Am. Bull.*, 85, 1931-1944, 1974.
- Hamilton, W., and W. B. Myers, Cenozoic tectonics of the western United States, *Rev. Geophys.*, 4, 509-549, 1966.
- Hill, M. L., and B. W. Troxel, Tectonics of the Death Valley region, California, *Geol. Soc. Am. Bull.*, 77, 435-438, 1966.
- Hill, R. L., and D. J. Beeby, Surface faulting associated with the 5.2 magnitude Galway Lake earthquake of May 31, 1975, Mojave Desert, San Bernardino County, California, *Geol. Soc. Am. Bull.*, 88, 1378-1384, 1977.
- Humphreys, E. D., and R. J. Weldon, II, Kinematic constraints on the rifting of Baja, California, *Am. Assoc. Pet. Geol. Mem.* 47, in press, 1990.
- Longwell, C. R., Possible explanation of diverse structural patterns in southern Nevada, *Am. J. Sci.*, 258-A, 192-203, 1960.
- Lyzenga, G. A., K. S. Wallace, J. L. Fanelow, A. Raefsky, and P. M. Groth, Tectonic motions in California inferred from very long baseline interferometry observations, 1980-1984, *J. Geophys. Res.*, 91, 9473-9487, 1986.
- MacFadden, B. J., C. C. Swisher III, N. D. Opdyke, and M. O. Woodburne, Paleomagnetism, geochronology, and possible tectonic rotation of the middle Miocene Barstow Formation, Mojave Desert, southern California, *Geol. Soc. Am. Bull.*, 102, 478-493, 1990.
- Meisling, K. E., and R. J. Weldon, Late Cenozoic tectonics of the northwestern San Bernardino Mountains, southern California, *Geol. Soc. Am. Bull.*, 101, 106-128, 1989.
- Minster, J. B., and T. H. Jordan, Present-day plate motions, *J. Geophys. Res.*, 83, 5331-5354, 1978.
- Minster, J. B., and T. H. Jordan, Vector constraints on Western U. S. deformation from space geodesy, neotectonics, and plate motions, *J. Geophys. Res.*, 92, 4798-4804, 1987.
- Minster, J. B., T. H. Jordan, P. Molnar, and E. Haines, Numerical modelling of instantaneous plate tectonics, *Geophys. J. Royal Astr. Soc.*, 36, 541-576, 1974.
- Morton, D. M., F. K. Miller, and C. C. Smith, Photo-reconnaissance maps showing young-looking fault features in the southern Mojave Desert, California, U. S. Geol. Surv. Misc. Field Stud. Map, MF-1051, 1980.
- Plescia, J., and T. L. Henyey, Geophysical character of the proposed eastern extension of the Garlock fault and adjacent areas, eastern California, *Geology*, 10, 209-214, 1982.
- Prescott, W. H., J. C. Savage, and W. T. Kinoshita, Strain accumulation rates in the western United States between 1970 and 1978, *J. Geophys. Res.*, 84, 5423-5435, 1979.
- Sauber, J., W. Thatcher, and S. Solomon, Geodetic measurement of deformation in the central Mojave Desert, California, *J. Geophys. Res.*, 91, 12,683-12,694, 1986.
- Sieh, K. E., and R. H. Jahns, Holocene activity of the San Andreas fault at Wallace Creek, California, *Geol. Soc. Am. Bull.*, 95, 883-896, 1984.
- Stewart, J. H., Extensional tectonics in the Death Valley area, California: Transport of the Panamint Range structural block 80 km northwest, *Geology*, 11, 153-157, 1983.
- Stock, J., and P. Molnar, P., Uncertainties and implications of the Late Cretaceous and Tertiary position of North America relative to the Farallon, Kula, and Pacific plates, *Tectonics*, 7, 1339-1348, 1988.
- Weldon, R. J., and E. Humphreys, A kinematic model of southern California, *Tectonics*, 5, 33-48, 1986.
- Weldon, R. J., and K. Sieh, K., Holocene rate of slip and tentative recurrence interval for large earthquakes on the San Andreas fault, Cajon Pass, southern California, *Geol. Soc. Am. Bull.*, 96, 793-812, 1985.
- Wesnousky, S. G., Earthquakes, Quaternary faults, and seismic hazard in California, *J. Geophys. Res.*, 91, 12,587-12,631, 1986.

R. K. Dokka and C. J. Travis, Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA 70803

(Received February 26, 1990;
revised May 9, 1990;
accepted May 17, 1990.)