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Triggered Surface Slips in the Coachella Valley Area Associated with the 1992 Joshua Tree and Landers, California, Earthquakes

by Michael J. Rymer

Abstract The Coachella Valley area was strongly shaken by the 1992 Joshua Tree (23 April) and Landers (28 June) earthquakes, and both events caused triggered slip on active faults within the area. Triggered slip associated with the Joshua Tree earthquake was on a newly recognized fault, the East Wide Canyon fault, near the southwestern edge of the Little San Bernardino Mountains. Slip associated with the Landers earthquake formed along the San Andreas fault in the southeastern Coachella Valley.

Surface fractures formed along the East Wide Canyon fault in association with the Joshua Tree earthquake. The fractures extended discontinuously over a 1.5-km stretch of the fault, near its southern end. Sense of slip was consistently right-oblique, west side down, similar to the long-term style of faulting. Measured offset values were small, with right-lateral and vertical components of slip ranging from 1 to 6 mm and 1 to 4 mm, respectively. This is the first documented historic slip on the East Wide Canyon fault, which was first mapped only months before the Joshua Tree earthquake. Surface slip associated with the Joshua Tree earthquake most likely developed as triggered slip given its 5 km distance from the Joshua Tree epicenter and aftershocks. As revealed in a trench investigation, slip formed in an area with only a thin (<3 m thick) veneer of alluvium in contrast to earlier documented triggered slip events in this region, all in the deep basins of the Salton Trough.

A paleoseismic trench study in an area of 1992 surface slip revealed evidence of two and possibly three surface faulting events on the East Wide Canyon fault during the late Quaternary, probably latest Pleistocene (first event) and mid- to late Holocene (second two events).

About two months after the Joshua Tree earthquake, the Landers earthquake then triggered slip on many faults, including the San Andreas fault in the southeastern Coachella Valley. Surface fractures associated with this event formed discontinuous breaks over a 54-km-long stretch of the fault, from the Indio Hills southeastward to Durmid Hill. Sense of slip was right-lateral; only locally was there a minor (~1 mm) vertical component of slip. Measured dextral displacement values ranged from 1 to 20 mm, with the largest amounts found in the Mecca Hills where large slip values have been measured following past triggered-slip events.

Introduction

Geologic and geodetic documentation of triggered, aseismic surface slip following moderate to large earthquakes has enhanced our understanding of the exact locations of fault traces, fault interaction, and the mechanics of fault slip. Triggered surface breaks were documented in the Salton Trough following the 1968 Borrego Mountain earthquake (Allen *et al.,* 1972), the 1979 Imperial Valley earthquake (Fuis, 1982; Sieh, 1982), the 1981 Westmorland earthquake (Sharp *et al.,* 1986a), the 1986 North Palm Springs earthquake (Sharp *et al.,* 1986b; Williams *et al.,* 1988), and the 1987 Superstition Hills earthquake (Hudnut and Clark, 1989; Sharp, 1989). Cases of triggered slip are also known, for example, in central California, associated with the 1984 Morgan Hill earthquake (Schulz, 1985); and the 1989 Loma Prieta earthquake (Galehouse, 1990; McClelland and Hay, 1990).

Triggered fault slip was also associated with the 1992 Joshua Tree and Landers earthquakes. The slip associated with the Joshua Tree earthquake is important because it demonstrates activity on a newly recognized fault. Triggered slip associated with the Landers earthquake is important because it represents the fourth time triggered slip has been documented along the San Andreas fault in the southeastern Coachella Valley, and comparisons can be made on the locations and amounts of slip.

Shortly after the 1992 Joshua Tree and Landers earthquakes (summarized in subsequent sections) field investigations were made to search for tectonic and triggered fault slip. Separate investigations were made after the two events to gain information on the regional effects of the earthquakes. Searches following the Joshua Tree earthquake were directed primarily at finding primary tectonic surface rupture, none of which was found (Rymer, 1992). In addition to tectonic slip during the Landers earthquake (Sieh *et al.,* 1993; Hart *et al.,* 1993), triggered slip was reported along faults in the Mojave Desert, primarily the Pinto Mountain, Lenwood, West Calico, Pisgah, Galway Lake, and Upper Johnson Valley faults (Hart *et al.,* 1993), along the Superstition Hills fault (Bodin *et al.,* 1994; R.V. Sharp, oral comm., 1992), and along the San Andreas fault in southeastern Coachella Valley (Bodin *et al.,* 1994; this study). This report presents data on triggered fault slips associated with both the Joshua Tree and Landers earthquakes. In addition, a short description and interpretation is given of a paleoseismic study on the fault affected by the Joshua Tree earthquake.

Joshua Tree Earthquake

The Joshua Tree earthquake (M_w 6.1) of 23 April 1992 occurred in the Little San Bernardino Mountains and was the beginning of "the greater Landers earthquake sequence" (Hauksson *et al.,* 1993). It had a focal mechanism and aftershock pattern indicating a near-vertical fault striking N10°W (Nicholson and Hauksson, 1992; Hauksson *et al.,* 1993; Hauksson, 1994). Geodetic calculations suggest a maximum slip of about 0.8 m at hypocentral depth and an implied rupture radius of 6–8 km (Bennett *et al.,* 1995). This earthquake caused no primary surface rupture (Rymer, 1992) but was associated with minor triggered fault slip about 5 km west of the epicenter (Fig. 1).

Prior to 1990, the geology and structure of the western Little San Bernardino Mountains was sparsely studied. Gneissic rocks exposed in the area were mapped as either the Pinto Gneiss or the Chuckwalla Complex, both inferred to be pre-Cambrian in age (Miller, 1938, 1944; Rogers, 1961; Rogers, 1965; Hope, 1966; Dibblee, 1967). New geologic mapping and radiometric dating indicate the Pinto Gneiss and Chuckawalla Complex are plutonic in origin (as a series of migmatites) with Cretaceous U-Pb zircon ages (Wooden *et al.,* 1994; Matti *et al.,* 1994; Fleck *et al.,* 1997). Hope (1966) mapped northwest-southeast-striking dextral faults and defined the northwest Dillon shear zone. Rogers (1965) and Dibblee (1967) also mapped northwest-striking faults of the Dillon shear zone. More detailed studies in the Desert Hot Springs area by Proctor (1968) included approximately north-south faults that locally offset structures of the Dillon shear zone. In this study, I recognize the Dillon shear zone (Fig. 2) as offset by at least three north-south faults that extend through the Little San Bernardino Mountains.

The N-S faults mapped in this study include, from west to east, the Long Canyon (LCF), East Wide Canyon (EWCF), and West Deception Canyon (WDCF) faults; the EWCF and WDCF extend northward to where they step west and connect with the Burnt Mountain and Eureka Peak faults, respectively (Fig. 1), both of which ruptured tectonically during the 1992 Landers earthquake (Treiman, 1992; Hart *et al.,* 1993). The LCF, EWCF, and WDCF exhibit long-term right-oblique slip, with the west side down. These faults dip westward from about 55° to 85°.

Observations of Surface Breaks

Field searches for tectonic or triggered slip associated with the Joshua Tree earthquake began within an hour of the shock and continued intermittently for seven days. Initially I checked along the Banning, Mission Creek, and San Andreas faults in the Indio Hills area where I found only nontectonic extensional cracks near the faults and no evidence of surface slip. In the days following the event, I made traverses into the northwestern Little San Bernardino Mountains. I examined the epicentral area and areas to the north, west, and south of it. The only location with ground cracks not easily assigned to ground shaking or slumping (nonfaulting processes), was near the southern end of the EWCF (Fig. 3). I checked for surface breakage along all of the EWCF shown in Figure 3.

Discontinuous surface breaks formed along the southern EWCF over a distance of 1.5 km (Fig. 3). Breaks developed in four areas; the most continuous crack sets and those with the largest displacements developed in thin Quaternary fluvial deposits ponded along an antecedent dry stream bed cutting across the EWCF. Surface breaks formed in straight and right-stepping echelon patterns. Straight breaks extended along the fault trace for distances as long as about 8 m. Echelon fracture patterns developed at only a slight angle to the fault trend. The 1992 slip was dominantly right-oblique, west side down; at all but one of the sites in which offset was clear and measurable, the dextral component of slip was greater than the vertical component. Slip was determined by measuring the slip vector, the azimuth of the slip, the local strike of the fault, the vertical component of slip, and the direction of relative vertical motion. Measured offset values were small; right-lateral and vertical components of slip ranged from 1 to 6 mm and 0 to 6 mm, respectively (Fig. 3). The EWCF was revisited at site EWC1 (see following sections and Figs. 2 and 3), following the Landers earthquake, but no additional surface slip had occurred since the previous site visit.

Faults southeast of the epicenter, within a broad zone of aftershocks associated with the Joshua Tree and Landers earthquakes (Hauksson *et al.,* 1993; Hauksson, 1994), were not visited immediately after the Joshua Tree earthquake.

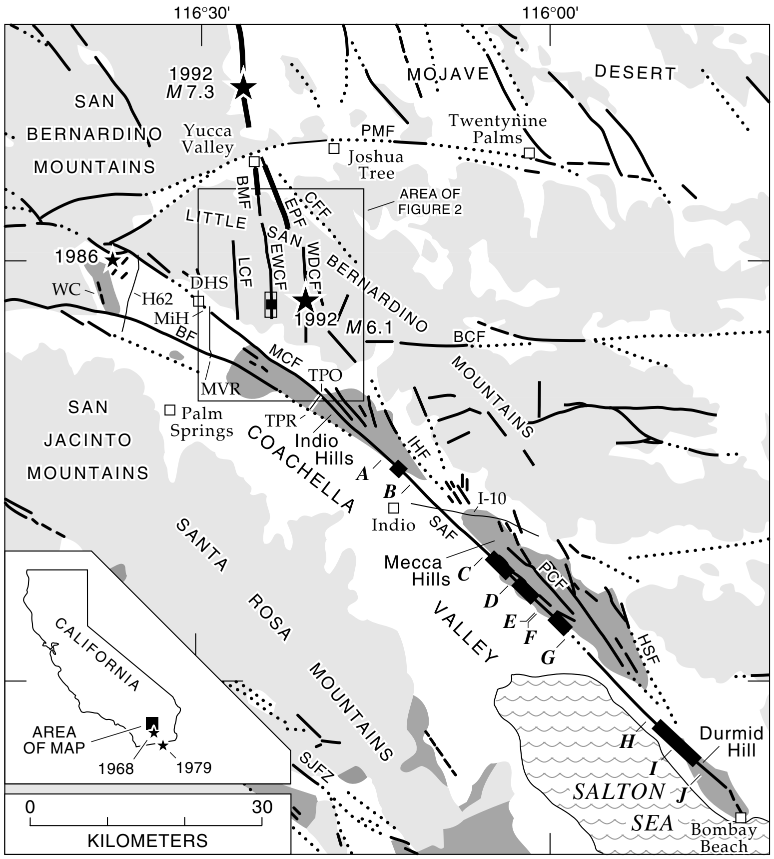

Figure 1. Index map showing Quaternary active faults and generalized geology in the greater southern San Andreas fault area (modified from Jennings, 1977, 1994; Powell, 1981). Heavy line, southern part of Landers surface faulting; Black bars show generalized location of surface slip along San Andreas fault triggered by the Landers earthquake. Large stars mark location of 1992 Joshua Tree and Landers main shock epicenters (labeled with magnitudes 6.1 and 7.3, respectively). Small stars with dates indicate epicenters of earlier earthquakes that also produced triggered slip on southern San Andreas fault (1968 and 1979 epicenters shown in inset). BCF, Blue Cut fault; BF, Banning fault; BMF, Burnt Mountain fault; CFF, Covington Flat fault; DHS, Desert Hot Springs; EPF, Eureka Peak fault; H62, State Highway 62; HSF, Hidden Springs fault; I-10, Interstate 10; IHF, Indio Hills fault; MCF, Mission Creek fault; MiH, Miracle Hill; MVR, Mountain View Road; PCF, Painted Canyon fault; PMF, Pinto Mountain fault; SAF, San Andreas fault; SJFZ, San Jacinto fault zone; TPO, Thousand Palms Oasis; TPR, Thousand Palms Road; WC, Whitewater Canyon. Light gray, crystalline rock; dark gray, stratified late Cenozoic deposits; white, Quaternary alluvium. Letters A to J mark location of ends of strip maps shown in Figure 7.

Many of these faults were visited and mapped three years after the event, in the spring of 1995. The near absence of Quaternary deposits, other than coarse bouldery rubble that fills canyon bottoms, made it unlikely that surface breaks would be found in this area of the Little San Bernardino Mountains so long after the event.

Other Phenomena Related to the Earthquake

The Joshua Tree earthquake triggered hundreds of landslides, especially in the Little San Bernardino Mountains and Indio Hills. The most numerous landslides were rock falls; there were also lesser amounts of soil falls. Abundant rock falls developed in the Little San Bernardino Mountains in association with the mainshock; numerous rock falls were also initiated by aftershocks in the following days. One site in particular, located about 4 km northeast of the mainshock, produced abundant rock falls for weeks after the event (M. Holler, written comm., 1992). Included in the number of earthquake-induced landslides are several along the San Andreas fault zone in southeastern Coachella Valley. Soil falls formed in Pushawalla Canyon and rock falls developed near Thousand Palms Oasis (C. Barrows, oral comm., 1992), both along the Mission Creek strand of the San Andreas fault. These two sites have respective distances from the Joshua Tree epicenter of about 12 and 13 km.

Many local residents also reported seeing earthquake lights. These claims were not substantiated by photographs or other documentation. Such reports came from residents of Sky Valley, located between the Indio Hills and the Little San Bernardino Mountains, and from near the Salton Sea. Residents of Sky Valley, located only 5–8 km south and southwest of the epicenter, reported lights from a general northerly direction (within the Little San Bernardino Mountains) at the time (9:50 p.m. local time) of the mainshock. No electrical wires or high-tension lines are present in the epicentral area, and there were no reports of downed power lines in that direction associated with the earthquake.

Residents of the Desert Hot Springs area also made anecdotal reports of water-level changes in wells and changes of water temperature in hot springs. However, all these claims are unsubstantiated. Water wells monitored on a monthly basis by a local water agency indicate no deviation from normal; unfortunately, all monitored wells are southwest of the Mission Creek fault (Ray Padgett, Mission Springs Water District, oral comm., 1996), whereas the reports of earthquake-related phenomena are from the northeast side of that fault.

Evidence of Prehistoric Slip

Subtle Holocene scarps, developed in overbank fluvial deposits, were noted along parts of the triggered slip on the EWCF. These scarps had the same sense of offset as the

Figure 2. Landsat TM satellite image of Little San Bernardino Mountains. Included in view are West Deception Canyon, East Wide Canyon, and Long Canyon faults; fault locations marked by unlabeled arrows. Epicenter of 23 April 1992 Joshua Tree earthquake marked by star. Location of trench (EWC1) across East Wide Canyon fault shown by labeled arrow. Northwest-striking faults of Dillon shear zone indicated by arrow labeled "NW"; poorly developed northeast-striking faults indicated by arrow labeled "NE".

vertical component of triggered slip. One scarp (Fig. 4) is marked by light gray cobbles to boulders on the east side and sand to pebbles on the west. An exploratory pit dug at the southern end of the scarp (Fig. 4B) exposed these deposits in cross section along with a wedge-shaped silt to sand deposit (shown between small vertical arrows in Fig. 4B) on the western, relatively downthrown side. The fine-grained deposit reaches a thickness of 12 cm and probably is of aeolian origin. The eastern, thicker, edge of the fine-grained deposit marks the location of the fault surface (indicated by a dashed line in Fig. 4B).

A shallow trench, trench EWC1, was dug 7 m south of the exploratory pit (Fig. 4) in order to see possible evidence of faulting within material finer than that found in the exploratory pit (Fig. 5). The excavation exposed medium- to coarse-grained sand and gravel fluvial deposits (Fig. 6). Trench logs of both the north and south walls of this 1.5-m-deep trench include a gneissic migmatite, which crops out

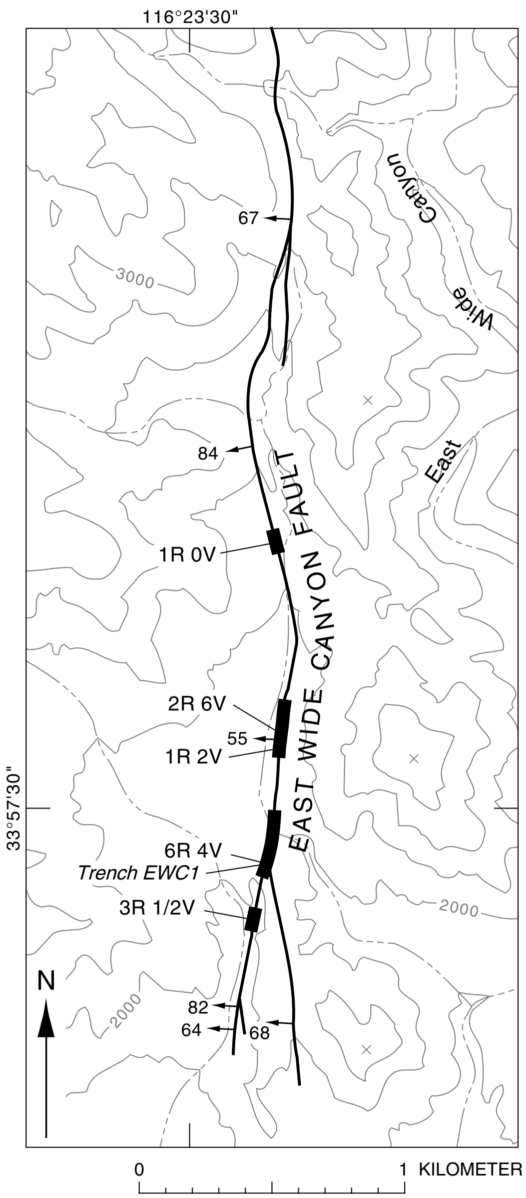

Figure 3. Southern part of East Wide Canyon fault area with locations of surface fractures (heavy line) associated with 23 April M_w 6.1 earthquake, measured slip values (R, right lateral; V, vertical, west side down, both in millimeters), and dip of fault (double-digit values). Base from U.S. Geological Survey, 1:24,000 scale, Seven Palms Valley, 1978.

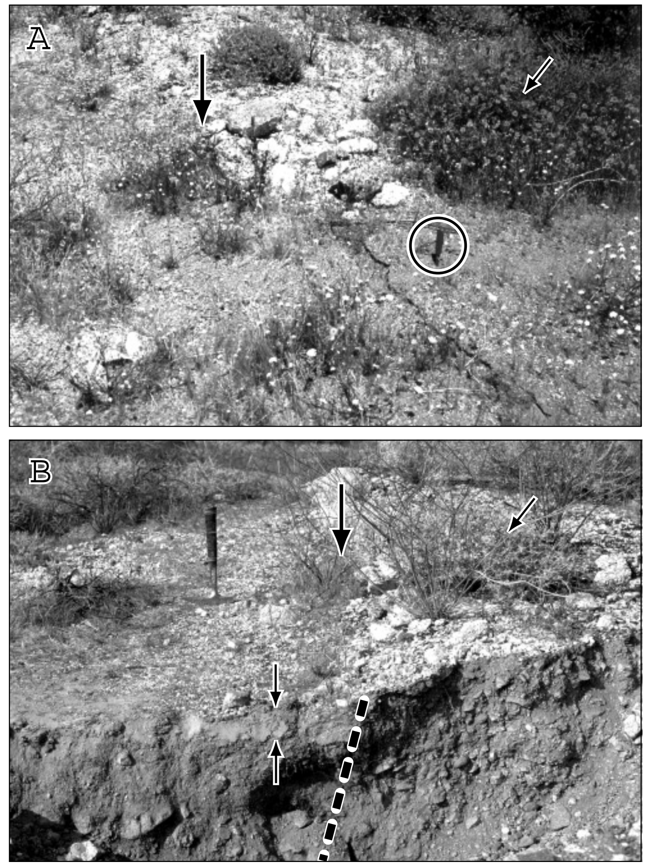

Figure 4. (A) Surface fractures along East Wide Canyon fault in association with 1992 Joshua Tree earthquake. Note location of fractures (marked by large vertical arrow) along west edge of subtle Holocene scarp; fractures extend to south, bottom right, of photograph. Pocket knife (circled) on east side of rupture for scale. Bush (defoliated in Fig. 4B) indicated by small oblique arrow. View to north-northeast; photograph taken 24 April 1992. (B) Shallow pit dug across scarp shown in Fig. 4A. View of scarp formed by pre-1992 earthquake(s) and ponded fine-grained sediment (between small vertical arrows in foreground) on west side of scarp. Scarp location and bush shown by large downward arrow and small left-diagonal arrow, respectively, mark same locations in both A and B. Rock pick on west side of scarp for scale. View to north; photograph taken 6 June 1994.

about 4 m east of the trench, at the base of the trench at its eastern end. The oldest sedimentary unit exposed in the trench, a moderately well cemented coarse-sand to pebbly-sand deposit (unit 4), is found only east of the fault. Higher in the section, and possibly above a disconformity, is a granule- to pebble-sandy gravel (unit 3) that constitutes the lowest unit exposed west of the fault. Above this unit is a slightly finer-grained granule- to coarse-sand deposit (unit 2). At the top of the section lies similar sediment with a poorly developed (young) soil (unit 1). Lithologic comparison of rocks exposed in the area suggests that unit 4 was locally derived from bedrock exposures east of the trench. Units 3-1 were derived predominantly from the west-northwest, as fluvial debris.

Because no dateable material was found in the trench, ages are estimated based on degree of cementation and soil development. Unit 4 is possibly late Pleistocene or early Holocene in age based on the degree of cementation and general difficulty of digging. I believe units 3-1 to be mid- to late Holocene in age based on the slight degree of soil development within these units.

Figure 5. View to south of south wall of trench EWC1, 7 m south of pit in Fig. 4B. Fracture formed in association with 1992 Joshua Tree earthquake indicated small arrow. Meter stick and scale card (inches on right; centimeters on left) shown for scale. Vertical line near shovel is meter mark. Photograph taken 8 June 1994.

One fault exposed in the trench extends through the sedimentary section to the ground surface, offsetting all the units and intersecting the triggered offset (arrows in Fig. 6A and B). This most recently active trace dips to the west about 80°, similar to nearby surface measures of fault dip (Fig. 3). Local splays from this "main" fault trace also offset sedimentary units, especially the vertical splay exposed in the south wall (Fig. 6A). Also exposed in the south wall is a poorly expressed fault located about 1 m west of the main trace. Apparent discrepancy of structure mapped in north and south trench walls may be due to discontinuous fault breaks or step-overs of minor, secondary fault splays.

Relations mapped in the trench walls suggest that at least two events ruptured to the surface (not including minimal slip in 1992). The following comments on offset and ratios of lateral-to-vertical offset assume planar tabular units, whereas exposures in the trench and the exploratory pit only 7 m to the north strongly suggest units are not planar or tabular: Unit 4, exposed on the east side of the fault, has no matching counterpart to the west. Thus, at least 60 cm of cumulative vertical-component slip is implied. Such slip would be associated with about 80 cm of right-lateral slip assuming lateral-to-vertical relations similar to that of the triggered offset, but this estimate is a minimum because matching parts of unit 4 are not found west of the fault. Such an event would post-date deposition of unit 4. Higher in the section, unit 3 is vertically offset about 35 cm in a narrow zone across the main trace of the fault, implying, as previously, a right-lateral component of about 50 cm. The lower sections of unit 2 are also cut and offset about the same amount. This fault may represent the most recent tectonic break along the EWCF. The causative earthquake would likely have occurred during or shortly after deposition of unit 2. Using the imprecise age assignments for units exposed in the trench walls, the event that initially offset unit 4 may represent a late Pleistocene to early Holocene event; the more recent event that offsets units 3 and the lower section of unit 2 may be mid- to late Holocene in age.

Discussion

The presence of triggered slip, details of the surface rupture, and style of slip along the EWCF provide new understanding of the nature and youthfulness of faulting in the western part of the Eastern Transverse Ranges. The approximately N-S-trending faults, LCF, EWCF, and WDCF, were tentatively mapped from aerial photographs prior to the 1992 Joshua Tree earthquake. The newly mapped surface slip and the focused field investigation following the earthquake document recent, probably Holocene, surface faulting along the EWCF. All three faults offset the northwest-striking Dillon shear zone and less well developed northeast-striking structures. Seismicity plots of the area prior to 1992 indicate seismic activity with an approximately N-S trend (Hill *et al.,* 1990).

Enough information exists to state that the 1992 surface slip along the EWCF was triggered slip. The location of the mainshock epicenter and the distribution of aftershocks (Hauksson *et al.,* 1993; Hauksson, 1994) indicates the Joshua Tree earthquake occurred on or to the southeast of the WDCF and not the EWCF, 5 km west. Even though the permanent seismic net used to locate the events is sparse relative to other areas, seismographs located in the Indio Hills and near the mouth of East Wide Canyon show first arrivals coming from a location to the east of the EWCF. Similar observations were made by Hough *et al.* (1993, 1994), who deployed seismographs in the area following the Joshua Tree earthquake, including a station directly at the mouth of East Wide Canyon. Even though their deployment postdates the Joshua Tree mainshock, their locations for large events coincide with the locations given by the regional net by Hauksson *et al.* (1993) and Hauksson (1994). Additionally, the N-S faults, including the EWCF and the WDCF, dip steeply to the west. Thus, seismicity reported about 5 km east of the surface trace of the EWCF definitely is not associated with down-dip projections of the EWCF. Other factors suggestive of triggered slip are the small displacement, less than or equal to 6 mm, and the discontinuous nature of surface breakage (see Fig. 3). Primary tectonic slip likely would rupture with larger amounts of offset, and while sometimes documented as discontinuous following other earthquakes, is not as spotty as that found along the EWCF. Finally, the cracks and offsets on the fault were not the result of downslope movement related to the strong shaking of the earthquake (Fig. 3); patches of surface slip formed on local topography with both south-and north-sloping surfaces. In summary, the aforementioned observations and recordings

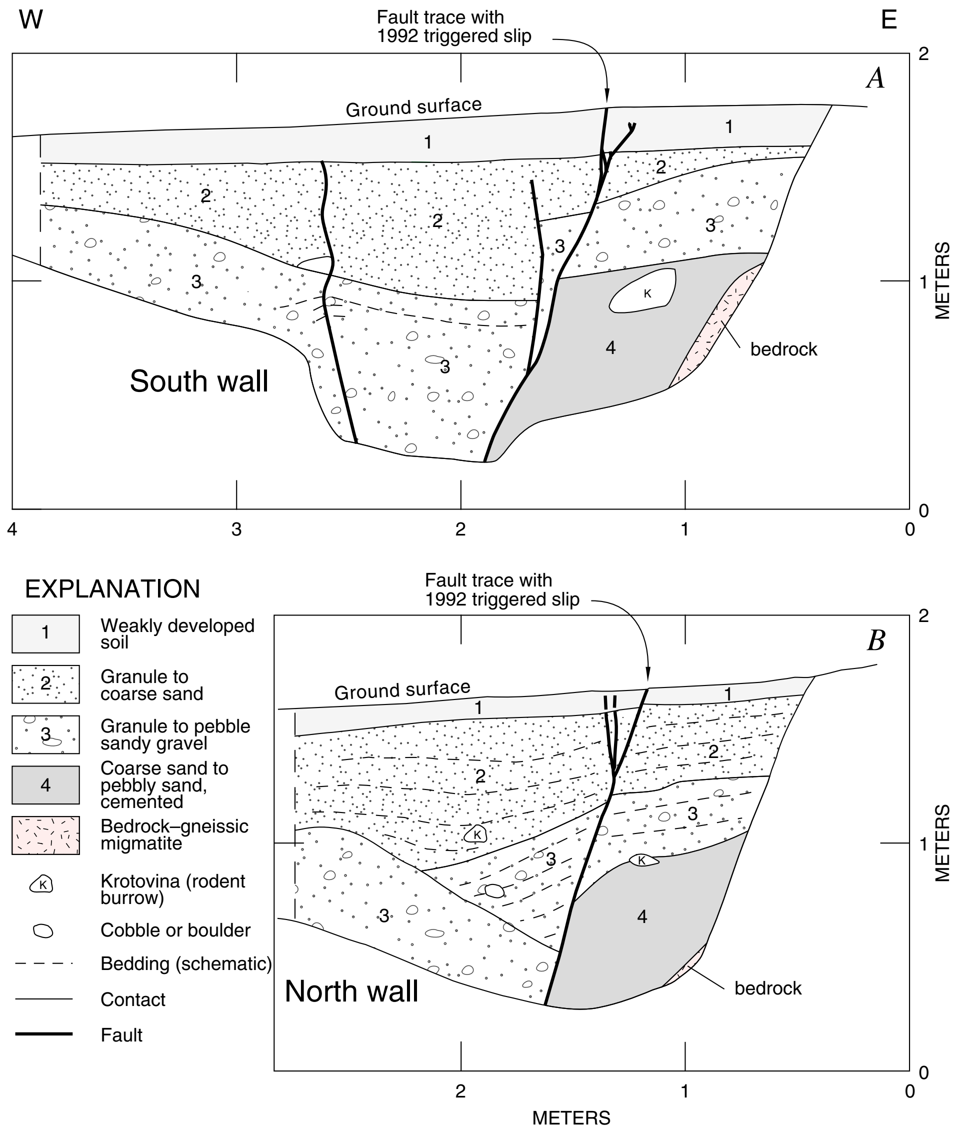

Figure 6. Northward view of logs of north and south walls of trench EWC1 (see Figs. 2 and 3 for location). (A) south wall; (B) north wall. K, rodent burrow (krotovina). See text for description of event horizons and event displacement.

strongly suggest the surface slip mapped along the EWCF was remotely triggered by the Joshua Tree earthquake.

Most previous geologic documentation of triggered slip has been along faults in deep alluvial basins, leading some investigators to speculate that the presence of thick alluvium is a prerequisite for formation of triggered slip (for example, Hudnut and Clark, 1989). Bodin *et al.,* (1994) speculated that thick alluviated basins may aid formation of triggered slip by amplifying seismic waves in poorly consolidated material. Such a process or others dependent on deep sedimentary basins may enhance formation of triggered slip, but given the surface breaks formed along the EWCF, one must conclude that this is not a critical element for development of triggered slip.

1992 Landers Earthquake

The Landers earthquake (M_w 7.3) of 28 June 1992 was the largest event of "the greater Landers earthquake sequence" (Hauksson *et al.,* 1993) and the largest shock in the contiguous 48 states in the past four decades. The earthquake was associated with about 70 km of primary surface rupture on four main faults, extending into the Mojave Desert primarily to the north-northwest (Hart *et al.,* 1993; Sieh *et al.,* 1993). Numerous other faults had minor surface breakage in association with the event (see Treiman, 1992; Hart *et al.,* 1993). Far-reaching effects of the earthquake include triggered seismicity throughout the western U.S. (Hill *et al.,* 1993) and triggered slip on distant faults, including the San Andreas fault in the southeastern Coachella Valley.

Many investigators checked traces of faults of the San Andreas fault zone west of Thousand Palms Canyon in the hours and weeks following the Landers earthquake, but found no evidence of triggered slip. For example, I checked traces of the Banning and Mission Creek faults across State Highway 62 about 8 hr after the event; many others checked the same locations earlier and later, but never reported surface slip. I also checked surface traces of both these faults along Mountain View Road, about 11 km east of State Highway 62, and near Thousand Palms Oasis; others stopped at the same sites and also found no evidence of surface-fault slip. Sylvester (1993) reported no detectable vertical slip at Miracle Hill, on the Mission Creek fault near Mountain View Road, or on the Banning fault at Whitewater Canyon, about 4 km west of State Highway 62. In contrast, there was evidence of fault slip farther to the southeast.

Field studies along the San Andreas fault southeast of Thousand Palms Oasis shortly after the Landers earthquake by other investigators (Sylvester, 1993; Bodin *et al.,* 1994; Shifflett and Witbaard, 1996) included geodetic, creepmeter, and geographically restricted observations, respectively. First-order leveling resurveys at four sites and remeasurement of horizontal distances in a trilateration array by Sylvester (1993) resulted in no detectable vertical or horizontal displacements at his survey locations within allowable uncertainty of less than 1 mm for leveling and about 2 mm for trilateration. Sylvester concluded that the Landers earthquake did not perturb the San Andreas fault at the surface in the Coachella Valley. However, in their study of creepmeter data recorded at four sites across the San Andreas fault in the Coachella Valley, Bodin *et al.* (1994) found that dextral slip was triggered within 1 min of the mainshock and that maximum slip velocities occurred 2 to 3 min later. Values of recorded dextral slip following the Landers earthquake varied at the instrument sites from about 0.2 to 10 mm (Bodin *et al.,* 1994). Shifflett and Witbaard (1996) reported 17 mm of dextral slip at a site along the San Andreas fault 2 km southeast of the mouth of Box Canyon, in the Mecca Hills. The present study includes a more comprehensive field survey of triggered slip associated with the Landers earthquake along the San Andreas fault, a brief analysis of the local triggered-slip history, and its possible causes.

Observations of Surface Breaks

Field checks made in this study for surface breakage along the San Andreas fault in southeastern Coachella Valley began on 7 July 1992, included parts of the days of 7, 9, 20, and 21 July 1992, and extended from Bombay Beach to the Indio Hills (Figs. 1, 7, and 8). On 16 March 1993 Judi Sheridan (University of Oregon) and I found additional surface breaks along an isolated section of the fault extending to the southeast for about 1 km southeast of Red Canyon that was not visited in the weeks following the earthquake.

Discontinuous surface breaks with consistent dextral slip formed over a distance of 54 km along the San Andreas fault, representing distances from the Landers epicenter of 54 to 105 km. Surface breaks formed primarily in three areas, the northwestern part of Durmid Hill, the central part of the Mecca Hills, and the southeastern part of the Indio Hills (Figs. 1, 7). Distances of greater than 10 km separate the three areas of observed surface breaks. With some exceptions, as discussed later, surface breaks formed in areas of uplifted, fine-grained Pleistocene lacustrine and fluvial deposits. Areas without breaks are characterized by late Quaternary alluvium, alluvial fan deposits, or modern stream-channel deposits. The 1992 slip was dominantly dextral; only locally in the Mecca Hills was a minor vertical component of slip measured.

Characteristics of surface breaks along the San Andreas fault include straight, continuous breaks over distances as great as about 10 m and echelon breaks. Echelon breaks varied in length with the angle to the local fault trend. For example, breaks with acute angles to the fault formed cracks ranging in length as great as a few meters; breaks more normal to the local fault strike formed short cracks in the range of a few tens of centimeters (Fig. 9). Locally, breaks formed as "mole tracks" where their orientation was nearly parallel to the local fault strike (see left side of Fig. 9). Also, "tent structures" formed between echelon breaks where rigid soil blocks or thin soil crusts were pushed up (Fig. 9).

Topographic changes along the fault had little effect on the development of surface breaks, except in the Durmid Hill area, between Bat Caves Buttes and a point about 2 km northwest of Salt Creek (Fig. 7). There, cracks were more prominent or more likely to be found on the northwest sides of small streams, even where the stream had widths of a meter or less.

Slip components were determined by measuring the displacement between matching irregularities in soil blocks or thin soil crusts along the local strike of the fault. Slip was determined by measuring the slip vector, the azimuth of the slip, and the local strike of the fault; where present, the vertical component of slip and the direction of relative vertical displacement were also measured. Offset values were small, nowhere greater than 20 mm (Figs. 7, 8).

The extent of triggered surface slip along the San Andreas fault zone in the Coachella Valley as shown in Figures 7 and 8 is limited by several factors. First, not all of the fault was examined following the shock. The lower panel in Figure 8 indicates the extent of the fault studied after the Landers earthquake. Certain stretches of the fault were not mapped for a several reasons: (1) surface breaks were not found for several hundred meters leading into an area not mapped, and (2) some areas were inaccessible following the earthquake, for example, much of the stretch between Quarry Canyon and Painted Canyon was not checked for surface breakage immediately following the earthquake, because rock falls blocked access through Red Canyon. Secondly, faults other than the San Andreas were not examined following the earthquake. Numerous faults with significant Quaternary and possibly Holocene displacement lie subparallel to the San Andreas in the Indio Hills, Mecca Hills, and

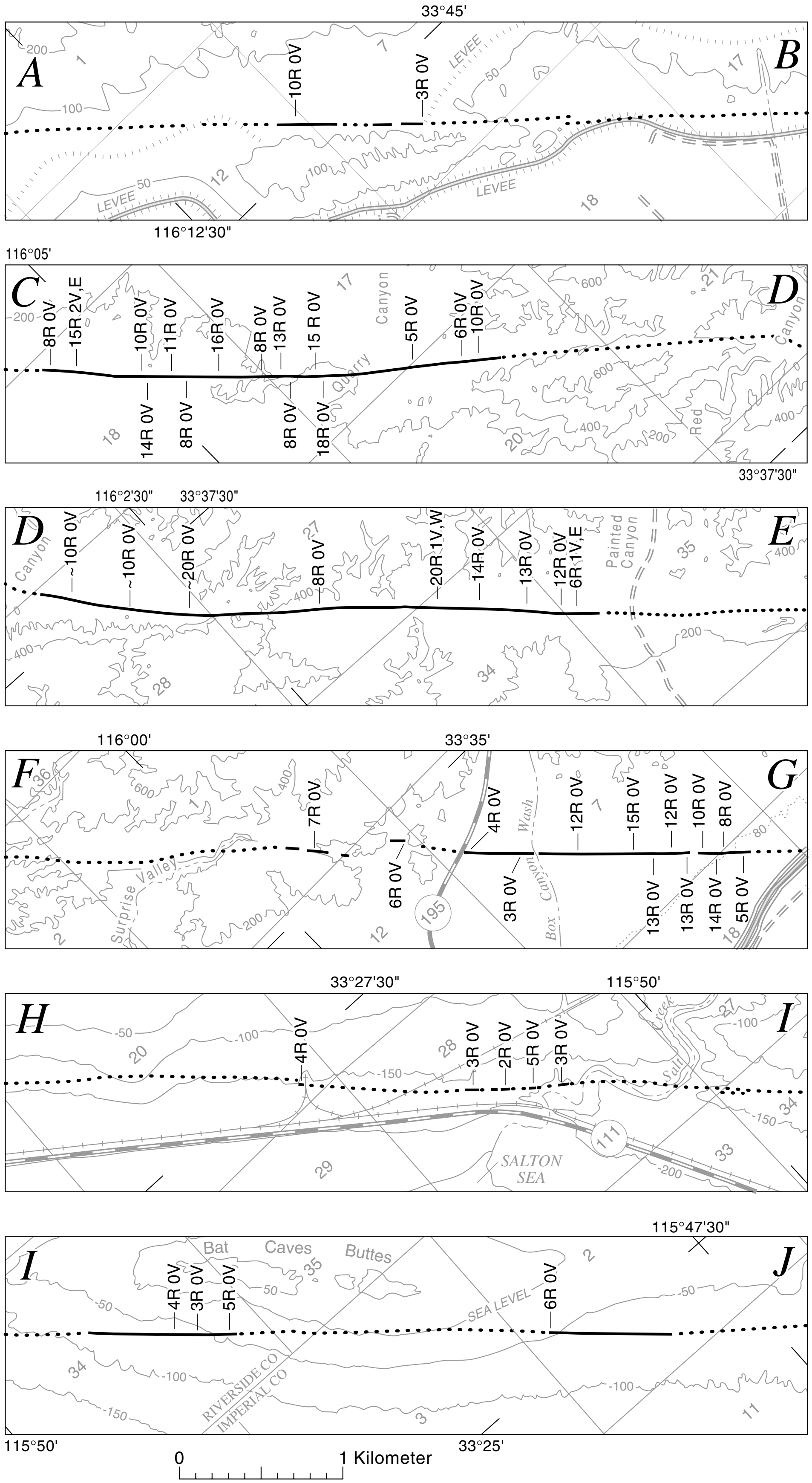

Figure 7. Caption on facing page.

Figure 7. Strip maps of San Andreas fault in Coachella Valley with location of surface fractures formed in association with 1992 Landers earthquake. Dotted line, San Andreas fault; solid line, location of documented 1992 surface fractures. [See Fig. 8 for location of searches for surface faulting.] Slip values shown in millimeters for both right-lateral (R) and vertical (V) components. Vertical components of slip, where present, are indicated with either west (W) or east (E) side up. Map strips derived using selected contours from topographic maps; location of strips shown in Fig. 1.

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Durmid Hill area (Clark, 1984; Jennings, 1994). Included in this group are the Indio Hills fault (checked in the spring of 1993), the Skeleton Canyon fault (checked in Box Canyon but not elsewhere until the spring of 1993), the Painted Canyon fault (checked in the spring of 1995), and the Hidden Springs fault, among others. The times of field checks are given above in spite of the long delay after the event because cracks were still visible elsewhere, although quite well rounded, as late as February 1995.

Timing of Triggered Slip

Both instrumental recordings and geologic observations constrain the triggered slip along the San Andreas fault to the time of the Landers earthquake and not earlier events such as the Joshua Tree earthquake. As discussed previously, Bodin *et al.* (1994) reported dextral slip that initiated within 1 min of the Landers mainshock at four creepmeter sites in the Coachella Valley. Dextral slip recorded by the creepmeters closely correlates with the amount of slip I measured at the ground surface.

Geologic constraints on the timing of crack formation are much more imprecise, but still worthy of mention for additional control on timing of dextral slip mapped at the ground surface. On the day of the Joshua Tree earthquake, I was mapping geology in the Red Canyon area of the Mecca Hills. After about one week of fieldwork in the Little San Bernardino Mountains following the Joshua Tree earthquake, I returned to the Red Canyon area, crossing the San Andreas fault at a slow pace on a daily basis. In those traverses I never noticed surface fractures along the fault. Additional fieldwork included driving across the San Andreas fault in Quarry Canyon. On the last field day in the Mecca Hills, 5 May 1992, a storm developed that resulted in significant downpour (NOAA, 1992) and sediment movement in the Mecca Hills. On trips back to the Mecca Hills following the Landers earthquake, about two months later, there were fresh, angular soil breaks, triggered slip (Fig. 9), in exactly the same active stream wash as had been driven in earlier, but without any tire marks. Presumably the storm on 5 May caused enough sediment movement to remove evidence of automobile and foot activity in the area. Therefore, the surface fractures found in the canyon represent triggered slip associated with the 28 June Landers earthquake and not the 23 April Joshua Tree earthquake.

Other evidence on the timing of crack formation comes from observations by Shifflett and Witbaard (1996), who were working in the Mecca Hills southeast of Box Canyon both shortly before and shortly after the Landers earthquake. On 6 June 1992 they did not observe cracks at their site; however, on 5 July 1992 they measured dextral slip as great as 17 mm at the same site (H. Shifflett, written comm., 1997).

Comparison of Geologic and Instrumental Measures of Triggered Slip

Creepmeters along the southern San Andreas fault that recorded slip associated with the 1992 Landers earthquake indicate both similarities and minor differences with the geologically determined slip. Bodin *et al.* (1994) pointed out that creepmeter-derived slip measurements are generally somewhat greater than geologic measurements made at the same site, probably because the creepmeters extend several meters on either side of the fault and thus include distributed shear that is not manifest on cracks. Also, the creepmeters are buried below the surface and thus are less affected by possible rotation of clasts that reduce apparent amounts of surface slip.

Direct comparisons of geologic and creepmeter measurements of triggered slip are possible at two of the four creepmeter sites, Salt Creek and North Shore. I observed no surface breakage directly at the Salt Creek creepmeter site, but I did measure 6 mm of discontinuous dextral slip about 20 m to the northwest. Bodin *et al.* (1994) calculated a 10 mm slip associated with the Landers earthquake at the Salt Creek creepmeter site. (See Bodin *et al.,* 1994, for discussion of problems with measurements at Salt Creek.) At the North Shore site I found no surface slip (Figs. 7, 8); Bodin *et al.* (1994) measured only minor (0.2 mm) dextral slip at the site.

Comparison of 1992 and Earlier Triggered Slips

Triggered slip in 1992 along the San Andreas fault in southeastern Coachella Valley generally occurred where it had in previous moderate earthquakes (Fig. 8). Each of the four documented slip events was triggered by seismic sources in very different azimuthal directions (see Fig. 1 and inset, Table 1); regardless, there are many similarities in rupture location and amount of offset. Earlier slip events associated with the 1968 Borrego Mountain earthquake (Allen *et al.,* 1972), the 1979 Imperial Valley earthquake (Sieh, 1982), and the 1986 North Palm Springs earthquake (Williams *et al.,* 1988), with only minor exceptions, formed in the Durmid Hill, Mecca Hills, and Indio Hills areas. These are areas where the fault is described by Bilham and Williams (1985) as more oblique to the regional slip vector and therefore more prone to experience slip. The largest slip in the two earliest events, 1968 and 1979, and in 1992, devel-

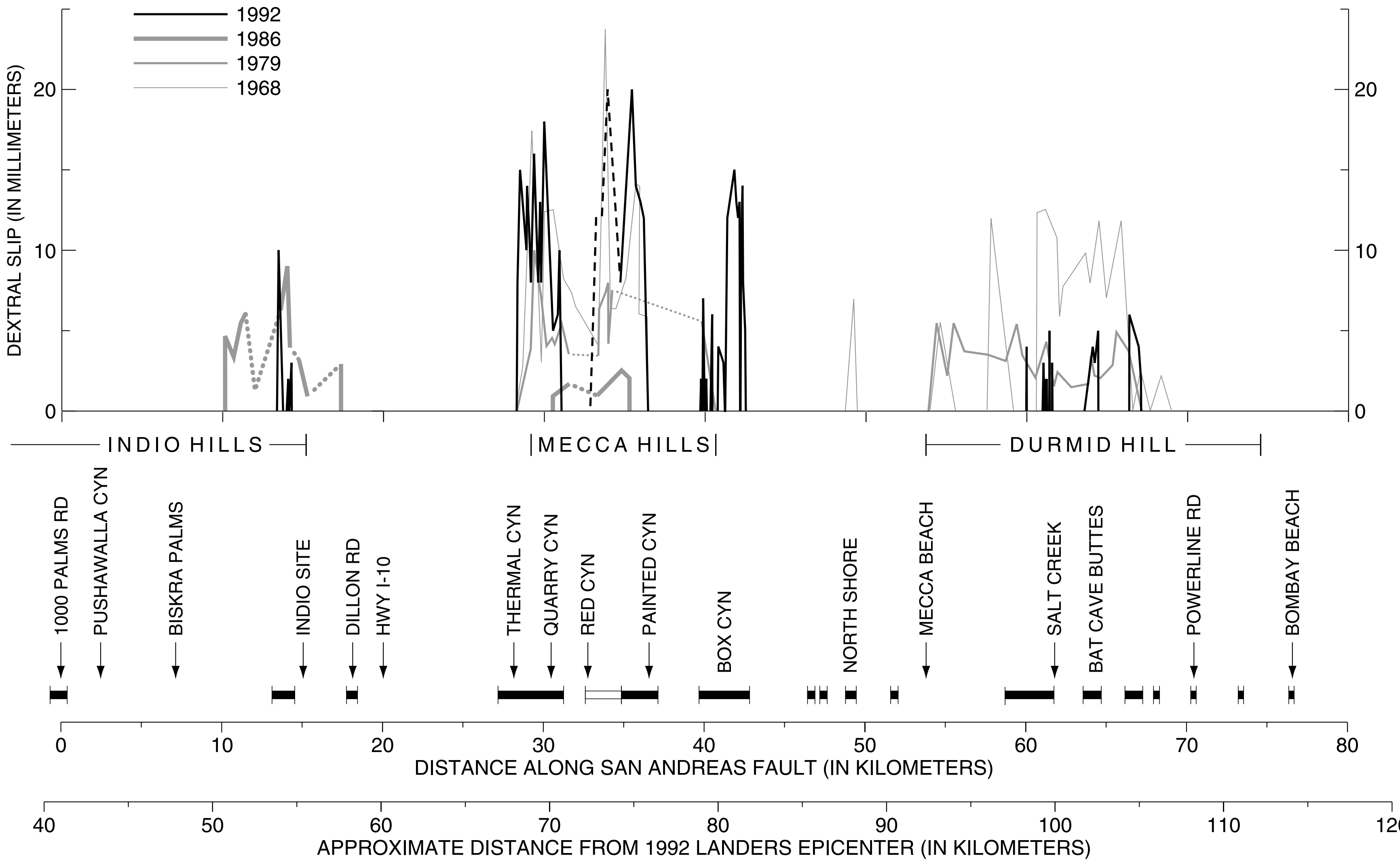

Figure 8. Right-lateral component of triggered slip as a function of distance along San Andreas fault. Distance scale along fault is relative to intersection of Thousand Palms Road and the San Andreas fault (see Fig. 1); distance scale from 1992 Landers epicenter is measured at an angle to fault strike. Horizontal bars above distance scale mark extent of searches for surface faulting. Open bar between Red Canyon and Painted Canyon marks area where cracks were first observed 16 March 1993 (described in text).

Figure 9. Triggered slip on San Andreas fault in modern wash of Quarry Canyon, with 18 mm of right-lateral component of displacement. Note left-stepping pattern of fractures and 'tent' structure that developed in thin crust of dried mud. Pencil indicates strike of fault. Photograph taken 7 July 1992.

Table 1

Characteristics of Triggered Slip Along San Andreas Fault in Southeastern Coachella Valley*

Year of Event	Magnitude (M_w)	Approx. Azmuthal Direction of Waves†	Extent of Triggered Slip along SAF‡ (km)	Distance to Epicenter‡ (km)	Maximum Slip Value (mm)
1968	6.5	335°–005°	41	35–45	24
1979	6.4	325°–335°	39	100–136	10
1986	6.0	120°–125°	25	44–86	9
1992	7.3	140°–150°	54	54–105	20

*Each of these events also triggered slip on other faults or on other parts of the San Andreas fault zone (for details see reports on individual earthquakes).
†Measured from epicenter to endpoints of triggerred slip.
‡Measured from southeast and northwest endpoints of slip; each slip event is associated with discontinuous slip (Fig. 8).

oped in the central Mecca Hills, between Painted Canyon and Thermal Canyon; the smaller North Palm Springs earthquake triggered the largest slip in the southeastern Indio Hills, but also broke the ground surface in the central Mecca Hills (Fig. 8).

Local, minor differences in locations of triggered slip in the four events are abundant; however, there are two major differences between the 1992 slip and earlier events. First, the 1992 event triggered slip over a greater distance along the San Andreas fault. Second, 1992 triggered slip included the stretch of the fault southeast of State Highway 195 (Fig. 7, strip map F–G) where slip has not been previously documented. This is an alluviated section of the fault across the mouth of Box Canyon toward the Coachella Canal and includes an offset Native American stone ring (Fig. 10). Slip values in the vicinity of the stone ring are fairly large, ranging from 13 to 17 mm (Figs. 7, 8).

Other Phenomena Related to the Earthquake

The Landers earthquake triggered hundreds of landslides over a broad area. Included in the number of earthquake-induced landslides were many along the San Andreas fault zone in southeastern Coachella Valley. Rock and soil falls created dust clouds rising from Pushawalla Canyon near the Mission Creek strand of the San Andreas (C. Barrows, oral comm., 1992), and numerous rock falls filled the stream

Figure 10. Triggered slip on San Andreas fault at offset stone ring, southeast of the mouth of Box Canyon, Mecca Hills. View northwest of fractures, marked by horizontal arrows, at a unique site and in section of fault where surface breakage had not been mapped in previous triggered-slip events. Pen in midground, marked by small diagonal arrow, for scale. Photograph taken 20 July 1992.

bed of Red Canyon in the Mecca Hills. These two sites are 43 and 72 km from the Landers epicenter, respectively.

Another feature worthy of mention is minor liquefaction that formed near Thousand Palms Oasis. Minor cracks and a small lateral spread formed in unconsolidated sand and silt along a creek margin in an area of about 30 m^2. This feature formed along the Mission Creek fault where the fault acts as a groundwater barrier, causing an anomalously shallow water table, less than 3 m below the ground surface (Johnson, 1993). Away from this site, the general lack of liquefaction effects associated with the 28 June earthquake is consistent with the great depth of the water table beneath the northwestern end of the Coachella Valley (see, for example, Tyley, 1974).

Discussion

The locations of triggered slip occurrences are generally consistent with modeled static stress changes (Harris and Simpson, 1992; Stein et al., 1992). Locations of triggered slip, including 1992 and earlier events (see also summation in Fig. 11) generally coincide with locations of uplifted lacustrine and fluvial deposits as described by Bilham and Williams (1985). The premise of their model is that contiguous fault segments, 12–13 km long, alternate in orientation between those parallel with the local plate slip azimuth and those more oblique to it, giving a "sawtooth" arrangement to the fault trace from the Durmid to Indio Hills. The more oblique segments are located in areas with higher topography and structurally uplifted strata; the more parallel segments are located in relatively low areas with Holocene alluvial cover. Most of the 1992 triggered slip occurred in oblique fault segments with one notable exception: the stretch of the San Andreas with triggered slip southeast of Box Canyon (Figs. 7, 8). According to the Bilham and Williams model, triggered slip at this location would be unlikely. However, a remeasure of the local orientation of the San Andreas fault in this stretch indicates a strike of N45°W, a segment more oblique to the plate slip vector; thus, the discrepancy with their model would disappear. Another exception is slip near North Shore, located approximately midway in a slip-parallel segment; the surface consists of uplifted, fine-grained sediment with only a thin veneer of alluvium, similar to the more oblique segments.

The nature of sediment in the more and less oblique sawtooth segments of the San Andreas fault may aid in understanding how slip is triggered and where it is found. New geologic mapping along the San Andreas fault in the Indio and Mecca Hills (M. Rymer, unpublished data, 1997; Sheridan and Weldon, 1994) shows structurally uplifted segments dominantly consist of early to mid-Pleistocene fine-grained lacustrine and fluvial deposits. Parallel and structurally low segments occur in dominantly coarse-grained alluvial fan debris. I speculate that the finer-grained materials retain water better, which may aid in formation of triggered slip through higher pore-fluid pressure. Or perhaps, in the alluviated areas, which contain coarse materials, clast rotation may obscure slip. Analogous variations from distinct scarps in rock or firm sediment to monoclinal warping in alluvium were observed by M.G. Bonilla for slip associated with the 1971 San Fernando, California, earthquake (U.S. Geological Survey Staff, 1971) and the Nuñez rupture associated with the 1983 Coalinga, Calif., earthquake (Rymer *et al.,* 1990). Exceptions to this tendency in oblique segments of the San Andreas fault in southeastern Coachella Valley, where coarse Holocene alluvium was broken, include: the northwestern end of Durmid Hill (1968, 1979); the mouth of Box Canyon (1992); the mouth of Quarry Canyon (1968, 1979, 1992); west of Quarry Canyon, extending toward the mouth of Thermal Canyon (1968, 1979, 1992).

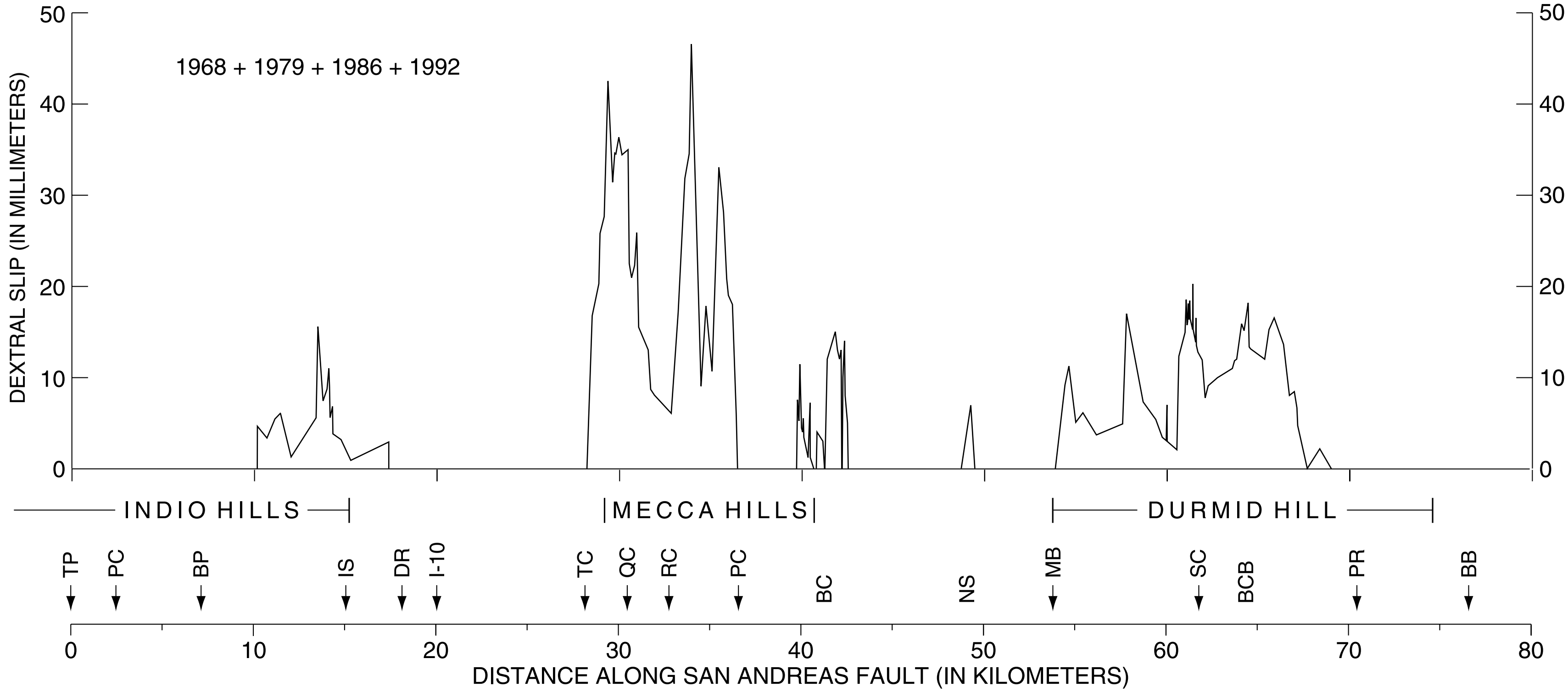

Figure 11. Cumulative right-lateral component of triggered slip from events in 1968, 1979, 1986, and 1992 as a function of distance along San Andreas fault. Horizontal scale and features along fault same as in Fig. 8; initials above scale bar correspond to locations named in Fig. 8; vertical-scale maximum is twice that in Fig. 8.

Conclusions

Triggered slip in association with the Joshua Tree earthquake, and the earthquake itself, significantly add to understanding the tectonic setting of the Little San Bernardino Mountains. The Joshua Tree earthquake developed along the West Deception Canyon fault, and triggered slip occurred about 5 km to the west on the subparallel East Wide Canyon fault; both faults were first mapped only months before the earthquake. The April 1992 activity on both faults convincingly proved suspected Quaternary activity for these structures. Triggered slip was small, with right-lateral and vertical components of slip ranging from 1 to 6 mm and 1 to 4 mm, respectively. The triggered slip formed discontinuously over a short (~1.5 km) distance along the fault, but its presence focused attention on a thin, less than 3 m thick, Holocene deposit with a subtle scarp.

Post-earthquake trenching studies revealed evidence of two and possibly three surface-rupturing events along the East Wide Canyon fault during late Quaternary time. The earliest of these events probably occurred in latest Pleistocene time; the second two events were probably in mid- to late Holocene time.

The Landers earthquake triggered surface slip in the Coachella Valley along the San Andreas fault. Dextral slip developed in discontinuous breaks over a 54-km-long stretch of the fault. Measured dextral displacement values ranged from 1 to 20 mm, with the largest amounts found in the Mecca Hills; only locally was there a minimal, ~1 mm, vertical component of slip. Comparison of triggered slip values associated with the Landers earthquake as determined geologically (about 1 m aperture) and by creepmeters (about 20 m aperture) not surprisingly indicate greater, ~3 mm, dextral slip amounts measured by creepmeters. Comparisons further show that creepmeter-determined slip reaches values of 3–5 mm before development of surface breaks for geologically determined slip. Creepmeter determinations of triggered slip are thus more sensitive to development of slip, but the value of geologically determined slip lies in the wide geographic distribution of measures and, where necessary, the significantly denser set of measures.

Within the past three decades triggered slip has been documented along the San Andreas fault in the southeastern Coachella Valley in four events, and in many additional geodetically determined aseismic slip events (e.g., McGill *et al.,* 1989; Williams and Sieh, 1987; Williams *et al.,* 1988), along with episodic dextral creep (Louie *et al.,* 1985; Sieh and Williams, 1990). If such surface movement has occurred throughout the period since the last great earthquake, about 300 years (Sieh, 1986), then the net displacement adds up to a significant amount of shallow strain release. In the central Mecca Hills, where geologically determined dextral slip alone totals about 50 mm in the past three decades (Fig. 11), assuming a similar displacement rate since the last earthquake would result in a net slip of approximately 50 cm. Earlier earthquakes that could have triggered slip since the last tectonic rupture along the southern San Andreas fault include the 1812 San Bernardino segment of the San Andreas fault, 1857 Mojave segment of the San Andreas fault, 1899 northern San Jacinto fault, 1915 northern Imperial fault, 1918 northern San Jacinto fault, 1940 Imperial fault, 1942 southern San Jacinto fault zone, 1948 Desert Hot Springs earthquakes, whether on the Mission Creek strand of the San Andreas fault zone or on the Banning strand as suggested by Nicholson (1996), and 1954 southern San Jacinto fault zone (see Hileman *et al.,* 1973). Large interseismic amounts of triggered slip could possibly confuse paleoseismic interpretations as to amount of slip per surface-faulting event and, when combined with episodic sedimentation, could lead to the interpretation of small surface-rupturing earthquakes when none actually occurred.

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