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TRIGGERED SLIP ALONG THE SAN ANDREAS FAULT AFTER THE 8 JULY 1986 NORTH PALM SPRINGS EARTHQUAKE

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Abstract

In addition to minor surface cracks in the region of the 8 July 1986 North Palm Springs earthquake, minor aseismic surficial rupture occurred along three segments of the San Andreas fault, 44 to 86 km southeast of the epicenter. Data from a creepmeter and a tiltmeter at one locality suggest that triggered slip occurred coseismically beneath the instruments but took 33 hr to propagate to the surface. That slippage occurred coseismically at depth favors mechanisms for triggered slip that involve dynamic or static strain changes rather than creep migrating from the source region.

The distribution of slip along the San Andreas fault associated with the North Palm Springs earthquake differed significantly from that recorded after the moderate 1968 Borrego Mountain, California and 1979 Imperial Valley, California, earthquakes. During these earthquakes, triggered slip occurred along the San Andreas fault in the Durmid Hill area and in the Mecca Hills. Triggered slip associated with the North Palm Springs earthquake occurred in these two areas again, but also extended farther northwest into the Indio Hills, where as much as 9 mm of dextral slip occurred. In the Mecca Hills, surface cracks in 1986 appeared over a shorter fault length than in previous events, and the dextral displacement was smaller, with maximum values of only 2 to 3 mm. On Durmid Hill, surface cracks in 1986 were localized along a 200-m-long stretch of the fault spanning the Mecca Beach creepmeter and extending about 150 m to the southeast. Right-lateral displacements on surface cracks in this area were 1.4 to 2.0 mm, smaller than those observed in previous events.

Although the mechanism of triggered aseismic slip is poorly understood, examination of displacement rates for the past several decades to centuries may indicate whether the aseismic slip rate is constant or represents accelerating premonitory failure of the southernmost San Andreas fault.

Introduction

The southern 200 km of the San Andreas fault, from Cajon Pass on the north to the Salton Sea on the south, has not generated a great earthquake for at least the past 175 yr (Agnew, 1985; Jacoby *et al.*, 1987; Williams and Sieh, 1987). However, geodetic evidence that the crust adjoining this fault segment is accumulating elastic shear strain at high rates (Thatcher, 1979; King and Savage, 1983) and paleoseismic evidence of large earthquakes during the past millennium (Sieh, 1986; Williams and Sieh, 1987) demonstrate the seismic potential of the southern San Andreas fault. The significance of low rates of aseismic fault slippage (Louie *et al.*, 1985) and triggered aseismic slippage along the southernmost 100 km of the fault following moderate earthquakes originating on nearby faults (Allen *et al.*, 1972; Sieh, 1982) is unknown. This study of triggered slip was undertaken in order to understand better the nature and significance of these phenomena.

Triggered slip associated with other earthquakes. Triggered aseismic slip was first documented after the moderate Borrego Mountain earthquake of 1968 (Allen *et al.*, 1972). Within 4 days of that event, the Imperial, San Andreas, and Superstition Hills faults experienced discontinuous surface slippage of up to 25 mm.

Triggered right-lateral slip was also observed soon after the Imperial Valley earthquake of 1979, a moderate temblor produced by rupture of the Imperial fault. Displacement was recorded on the San Andreas fault by Sieh (1982) and on the Superstition Hills fault by Fuis (1982). Sieh (1982) showed that as much as 10 mm of surficial slip occurred on the San Andreas and constrained the time of rupture to between one-third and 4 days following the main shock. Displacement on the Superstition Hills fault reached a maximum of 22 mm in the 1979 event.

Sharp *et al.* (1986a) observed up to 1 cm of dextral surface slip along a 17 km length of the Imperial fault and along a 16 km length of the Superstition Hills fault soon after the April 1981, M_L 5.6 Westmorland earthquake. Displacement was observed on the day of the earthquake along the Imperial fault and on the Superstition Hills fault within 2 to 4 days of the earthquake.

The Character of Surficial Slip in 1986

Soon after the earthquake of 8 July 1986, dextral surficial slip occurred on three sections of the San Andreas fault that lie between 44 and 86 km from the epicenter. These sections are labeled A-B-C, D-E-F, and Mecca Beach in Figure 1. Trace fracturing of a more ambiguous character occurred locally, near the epicenter (Sharp *et al.*, 1986b). The search for surficial fault slip was carried out along accessible sections of the San Andreas fault between central Durmid Hill and the southern Indio Hills, and was continued to within <20 km of the epicenter along the Mission Creek fault and to within <10 km of the epicenter along the Banning fault. The search for fault rupture was done from 14 to 20 July 1986. Sharp *et al.* (1986b) checked the Mission Creek and Banning faults in the epicentral region.

General slip features. The surface expression of triggered slip in 1986 was similar to that observed earlier by Allen *et al.* (1972), Fuis (1982), Sieh (1982), and Sharp *et al.* (1986a, b). Northwest-trending, left-stepping *en echelon* cracks with dextral slip were dominant, with east-trending compressional ridges sometimes present between these cracks. En echelon cracks ranged in length from 10 to 600 cm, but were usually shorter than 100 cm. Convergent segments were 5 to 50 cm in length. The width between adjacent dextral slip en echelon segments ranged from a few centimeters between the shortest cracks up to 500 cm between the longer cracks. Semi-continuous zones of surface slip ranged between 1 and 80 m in length. On older surfaces, the locations of 1986 slip zones coincided with preexisting tectonic landforms. Furthermore, cairns built on cracks in 1979 by Sieh and his students coincided with 1986 cracks at those sites where surface cracking occurred in association with both earthquakes.

Dextral offset measured across cracks along the San Andreas fault in July 1986 ranged from ≦1 to 9 mm. Slip was measured parallel to the trace of the San Andreas fault zone, between the northwest and southeast walls of pull-apart structures and between matching irregularities on the edges of en echelon cracks.

Slip distribution. The southernmost cracks were at Mecca Beach, 86 km southeast of the epicenter (Figures 1 and 2). Zones of cracks 1 to 4 m long were separated by 5- to 35-m-long unbroken sections. Ground cracks extended for 200 m along a zone centered about 50 m to the southeast of the Mecca Beach creepmeter.

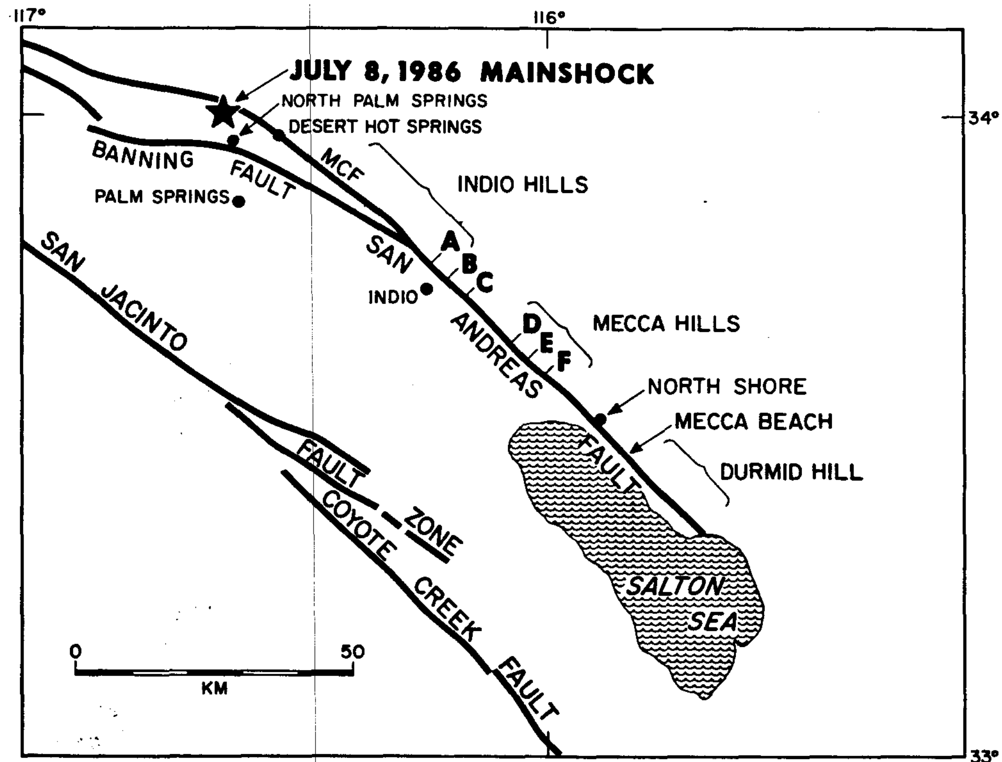

FIG. 1. Reference map for triggered slip along the San Andreas fault associated with the North Palm Springs earthquake. The southernmost San Andreas fault extends southeastward from the Indio Hills to the Salton Sea. The 8 July 1986 main shock epicenter is shown by a star. In the epicentral area, the San Andreas system consists of the Mission Creek (MCF) and Banning faults. Minor surface rupture of the San Andreas fault occurred in the southern Indio Hills between A and C, in the Mecca Hills between D and F, and at Mecca Beach. The zones of surface displacement across the San Andreas fault were between 44 and 86 km from the epicenter.

Dextral slip of 1.4 to 2.0 mm was measured on surface cracks on the morning of 16 July.

The zone of fracturing in the Mecca Hills was 5.5 km long (Figures 2 and 3). Cracks were observed between Painted Canyon Road and the Thermal Canyon fan. Along segments where slip occurred in both 1986 and 1979 or 1968, dextral offsets of 1986 were less than those measured in 1979 or 1968. Discontinuous sections of ground cracks occurred along a 1.5 km length southeast of Red Canyon (Figures 2 and 3). Maximum dextral displacement of 2 to 3 mm occurred within ½ km of the southern extent of rupture, and slip in this area gradually decreased to <1 mm toward the northwest. A 3.2-km-long zone without surface slip extended from Red Canyon to Quarry Canyon. Within Quarry Canyon wash, and for 0.7 km to the northwest, there were zones of en echelon cracks up to 70 m long. Maximum slip was 2 mm within the wash, and slip decreased to <1 mm toward the northwest.

Slip between Biskra Palms and the Coachella Valley Water District irrigation canal northeast of Dillon Road was as great as 9 mm (Figures 2 and 3). This was the greatest right-lateral displacement that we observed. Tectonic cracks had not been described previously in the Indio Hills, although other evidence of ongoing aseismic slip had been collected within this section; an alignment array at Dillon

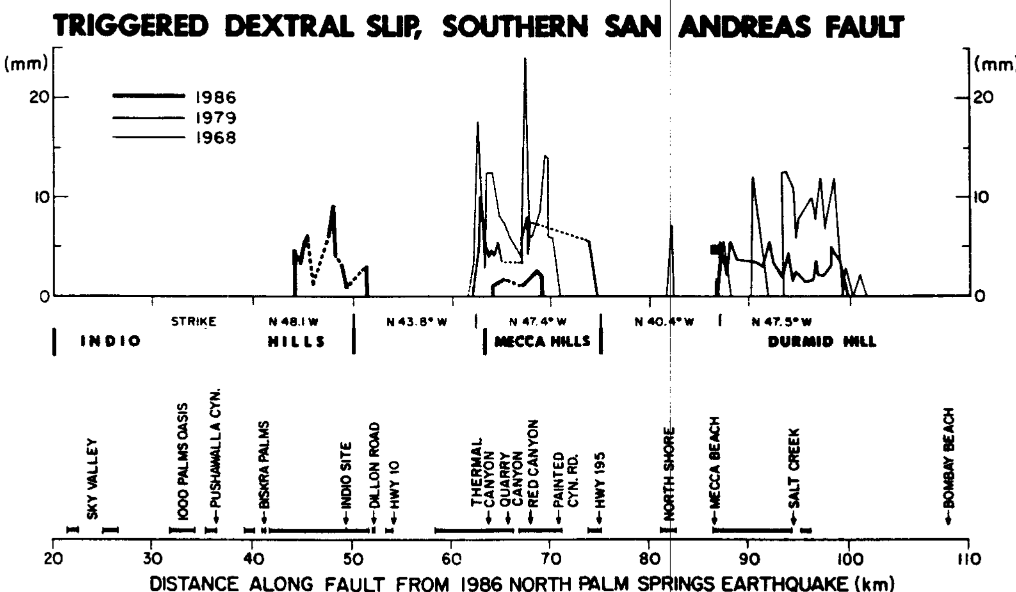

FIG. 2. Triggered dextral slip plotted along the San Andreas and Mission Creek faults. Horizontal axis is marked with the distance from the 1986 epicenter measured along the San Andreas and Mission Creek faults. Fault displacements in 1968 and 1979 are modified from Bilham and Williams (1985, their Figure 2). Short gaps between areas that have experienced semi-continuous dextral rupture are connected by dashed lines. Also presented are strikes for five segments of the San Andreas and Mission Creek faults and the locations of the Indio, Mecca, and Durmid Hills. Segments reconnoitered for ground cracks in July 1986 are represented by a discontinuous bold line above the horizontal scale.

Road recorded dextral slip of 2 ± 1 mm/yr between April 1970 and February 1984; an additional alignment array in the southern Indio Hills recorded 1.8 mm/yr during that time interval (Louie *et al.*, 1985). As elsewhere, cracks along the Indio Hills section closely followed geomorphic evidence of previous slippage.

Mecca Beach creepmeter and tiltmeter. A creepmeter and a tiltmeter are located near the Mecca Beach campground. This was the southernmost locality at which cracks were observed in 1986. The Mecca Beach installation consists of an 11.6-m-long taut-wire extensometer [see Cohn *et al.* (1982) for a description] and a Kinemetrics bubble tiltmeter. The data from both instruments are telemetered to Caltech daily. En echelon cracks with right-lateral surface slip were noted in the vicinity of the Mecca Beach creepmeter on the morning of 14 July.

Figure 4 shows the telemetered records from the creepmeter and tiltmeter, as well as the temperature measured in the instrument vault, for a 20-day period following the earthquake. In the figure, a geometric correction has been applied to convert the extension measured by the creepmeter to slip resolved onto the fault plane. No temperature corrections have been applied to the data in the figure, but the slip values reported in the following paragraphs have been corrected for the change in wire length due to temperature effects.

The temperature correction is calculated by first determining the change in average temperature between the start and finish of the creep event. This temperature change is then multiplied by a temperature correction factor (0.018 mm/°K) that was determined by analyzing the Mecca Beach creepmeter response to diurnal temperature fluctuations. The apparent slip that would be recorded by the creepmeter due to the observed temperature change is thus calculated and subtracted from the observed slip.

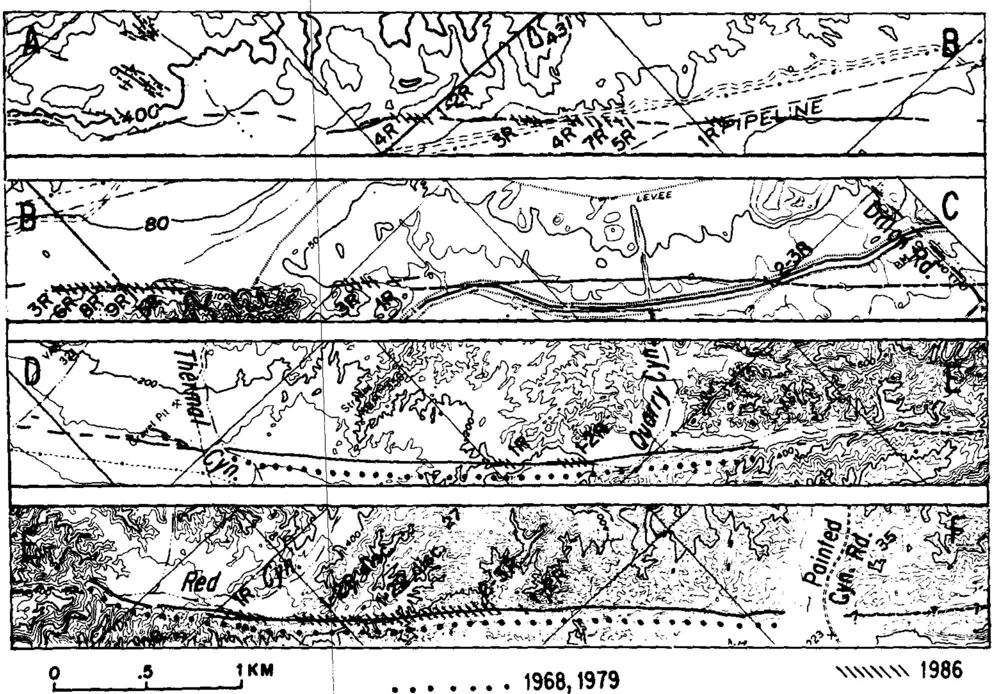

FIG. 3. Strip maps of the trace of the San Andreas fault (modified from Clark, 1984). The endpoints A-B-C and D-E-F correspond to letters on Figure 1. A-B-C lies along the Indio Hills segment in the area between Biskra Palms and Dillon Road. D-E-F is located in the Mecca Hills from the Thermal Canyon fan to Painted Canyon Road. The left-stepping *hatchure pattern* corresponds to zones of surface rupture in 1986, which in all cases were located on or very close to the fault trace as mapped by Clark. The magnitude of right-lateral slip in 1986 (in millimeters) is indicated by a number, or range of numbers, followed by the letter R. Locations of slip along the fault in 1968 or 1979 are indicated by dots. For clarity, the dots have been plotted southwest of the fault, but slip actually occurred along the fault trace as mapped by Clark (1984).

The creepmeter recorded a total of 5.0 mm of slip, occurring in two creep events. The creep events displayed a rapid onset and an exponential decay, as is characteristic of episodic creep events observed in central California (see, e.g., Evans *et al.*, 1981). The first creep event began at 11:30 a.m. PDT on 9 July 1986, about 33 hr after the North Palm Springs earthquake. This event had a dextral displacement of 1.9 mm. The creep event was preceded by tilting that began at the time of the earthquake. The tilt direction then changed from down to the northwest to down to the southeast about 11 hr prior to the arrival of the creep event at the surface. This suggests that the creep event actually began at depth immediately after the earthquake and propagated to the creepmeter in the following 33 hr. The change in tilt direction represents the lateral migration of the creep event beneath the tiltmeter. McHugh and Johnston (1976) modeled similar reversals in tilt direction as the propagation of a dislocation surface along the strike of a fault.

The second creep event began at 4:34 p.m. PDT on 13 July 1986, 5.5 days after the North Palm Springs event and 9 hr after the M_L 5.4 Oceanside earthquake, the epicenter of which was 196 km to the southwest. This creep event involved 3.1 mm of dextral slip. This creep event also was accompanied by tilting, but the tilting began at the same time as initiation of the creep event. This coincidence suggests that the second creep event began at or very near the surface.

A third creep event was recorded beginning at 1:31 a.m. PDT on 22 July 1986.

A tilt event preceded the creep event by 9 hr. Several lines of evidence indicate that this third creep and tilt event may not be of tectonic origin. The State Division of Forestry in the nearby settlement of North Shore reported 0.90 inches of rain between 3:30 and 6:30 p.m. on 21 July 1986. The apparent tilt event began at 4:30 p.m. on 21 July and thus may be a response to the rain. Wood *et al.* (1973) have described the strong effects of rain on tiltmeters.

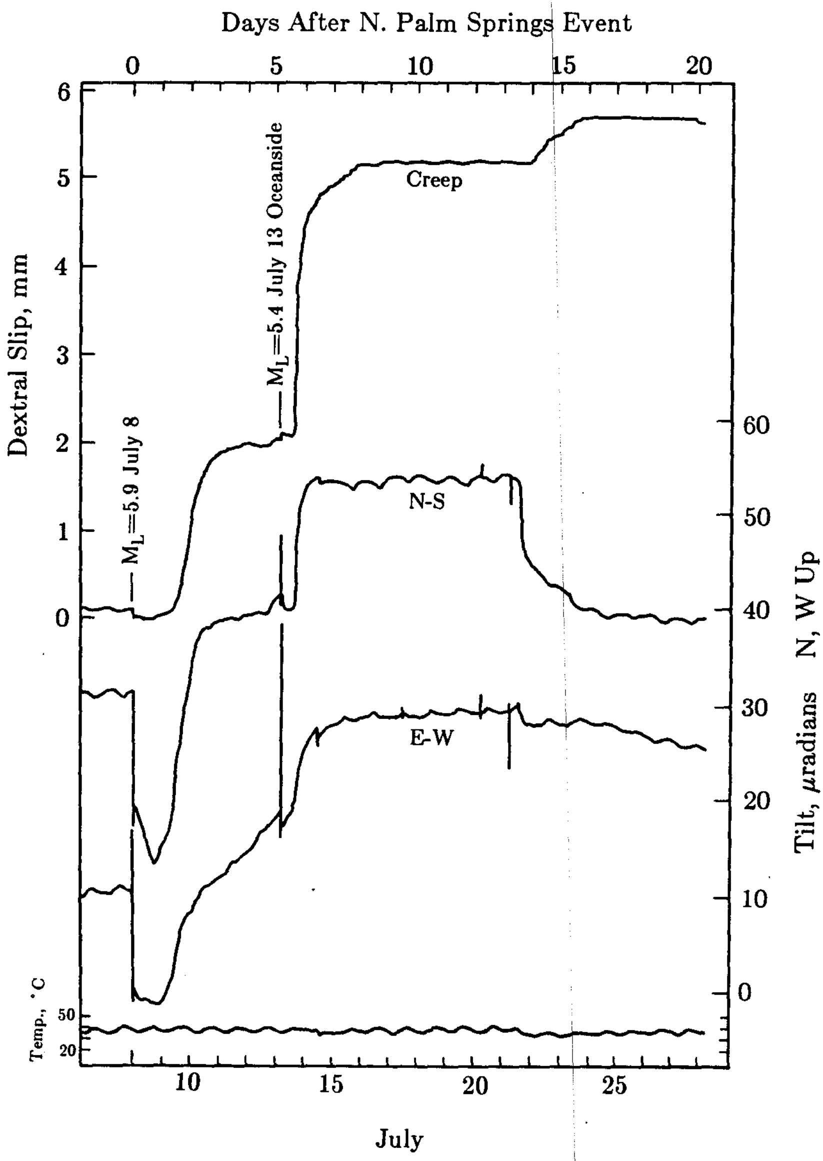

FIG. 4. Telemetered records from creepmeter and tiltmeter at Mecca Beach for a 20-day period following the North Palm Springs earthquake. Tilt scale (μ radians) is plotted on the *right*. Dextral slip (mm) and instrument-vault temperature (°C) are plotted on the *left*. Day marks along the horizontal axes are 24-hr intervals after the 2:20 am (PDT) main shock of the North Palm Springs earthquake. A geometric correction factor has been applied to the creepmeter record to yield slip parallel to the fault (N45°W). No correction for the change in wire length with temperature has been applied to the data in the figure. Creepmeter displacements reported in the text, however, are temperature-corrected values.

The apparent dextral creep event of 22 July may have been a response to the large temperature drop that accompanied the rain. Although the creepmeter recorded 0.5 mm of apparent dextral slip during the third event, much or all of this may be due to the temperature drop or to shifting of the soil in response to the rain. Application of the temperature correction as described previously, results in a 0.1 mm reduction of dextral slip in the third event. However, as also mentioned, the temperature correction used is based on the response of the creepmeter to diurnal temperature fluctuations. For fluctuations of such short periods, the creepmeter does not have time to fully equilibrate to the peak temperatures. However, the temperature drop that accompanied the apparent third creep event lasted for several days, so the creepmeter may have responded more dramatically than it would to diurnal fluctuations. For this reason, we believe that for the third creep event the temperature correction factor does not fully remove the part of the signal due to temperature effects. Thus, the actual amount of creep was probably less than 0.4 mm and may have been zero.

Support for this interpretation is also found by noting that 80 per cent of the apparent slip in this third event was recovered over the following 2 weeks as the temperature gradually rose back to its former level. Furthermore, the form of this third creep event does not display the rapid onset and exponential decay that is characteristic of other episodic creep events.

The timing of the third tilt and creep events, 8.8 and 17.8 hr, respectively, after the M_L 6.4 Chalfant Valley earthquake 500 km to the north of Mecca Beach is intriguing. However, the observation that the third disturbance of the Mecca Beach monitoring equipment is closely associated with both rainfall and falling temperature, and that the recovery of apparent slip corresponds to slowly rising temperature, indicates that it was caused by the local weather phenomena and was not a tectonic effect of the distant earthquake.

Distributed slip. The amount of slip recorded by the Mecca Beach creepmeter is two to three times the amount measured across fractures at Mecca Beach. The slip across the fractures was measured the morning of 16 July, just after the creepmeter recorded the end of the second slip event. It is possible that the creep event had fully reached the creepmeter at this time, but fault rupture had not completely migrated the additional 1 m or so to the surface. However, a more likely explanation for the discrepancy is that not all of the slip occurred on the observed ground fractures. Some slippage may have been distributed in a broader zone about the fault but still within the 11.6 m span of the creepmeter.

Discussion

Triggering mechanism. Four possible mechanisms for triggered slip have been suggested by Allen *et al.* (1972) and Fuis (1982). These are: (1) a change in the static strain field associated with a distant fault rupture; (2) the dynamic strain associated with the passage of seismic waves; (3) creep migrating from the source region; and (4) a regional strain event at depth that is manifested as seismicity in one area and as aseismic slip in another area. In the case of slip triggered on the San Andreas fault by the 1968 Borrego Mountain earthquake, Allen and others (1972) showed that the change in the static strain field was an order of magnitude less than the dynamic strain due to ground shaking, so they preferred the mechanism of dynamic strain over that of static strain.

The creepmeter and tiltmeter records of July 1986 at Mecca Beach have provided the first detailed record of the timing of triggered slip events, and this timing has important implications for the possible triggering mechanisms. In particular, the data from the Mecca Beach creepmeter and tiltmeter are not consistent with the triggering mechanism of creep migrating from the source region of the triggering event. First, migration of creep from near North Palm Springs to Mecca Beach would require propogatation of an aseismic dislocation over a distance of 86 km, a much greater length of propagation than has been observed along the segment of the San Andreas fault in central California that exhibits episodic creep (Evans *et al.*, 1981). Second, the coseismic, or immediately post-seismic tilt signal indicates that slip occurred in the vicinity of Mecca Beach immediately (8 ± 9 min) after the earthquake, even though it did not occur at the creepmeter for 33 hr. Thus, in the case of the first creep event, the triggered slip occurred essentially at the time of the earthquake and could not have been triggered by creep migrating from the source region.

Factors controlling the amount of triggered slip. Sharp *et al.* (1986b) present data which suggest that "sympathetic slip" on a creeping fault may occur in a creep-deficient surficial layer. The data accumulated by the Mecca Beach creepmeter also suggests that the amount of slip that occurs in a triggered creep event is controlled in part by the size of this slip deficit as explained later.

Several creep events were recorded by the Mecca Beach creepmeter between April and July 1984. Total dextral offset during these events was 9.0 ± 0.6 mm. In addition, the creepmeter measured slip at an average rate of 0.7 mm/yr from May 1981, when the instrument was installed, up to the time of the April 1984 creep event. If we assume that a creep rate of 0.7 mm/yr applies to the period between the 1979 triggered slip and the installation of the creepmeter in 1981, this indicates that a slip rate of 2.56 mm/yr applies for the period extending from just after the 1979 earthquake to just after the 1984 creep events.

If potential slip continued to accumulate at 2.56 mm/yr after the 1984 creep events, then a slip deficit of 5.1 mm could be expected to accumulate in the surficial layer between the 1984 creep events and the 1986 creep events. The creepmeter recorded only 0.2 mm of steady, aseismic creep between the 1984 and 1986 creep events, so the expected slip deficit at the time of the North Palm Springs earthquake was 4.9 mm. This compares favorably with the 5.0 mm of slip triggered by the North Palm Springs earthquake. Of course this close agreement is dependent on the assumption of a 0.7 mm/yr creep rate for the 1.6 yr period between the Imperial Valley earthquake and the installation of the creepmeter in May 1981. However, moderate errors in the assumed creep rate for this period have a small effect on the expected slip deficit. For example, if the creep rate was 0 or 1.4 mm/yr, the expected slip deficit would be 4.5 or 5.4 mm, respectively. These values remain very close to the observed slip of 5.0 mm.

Slip occurred again at Mecca Beach in the fall of 1987, and was probably associated with the 23 and 24 November M_L 6.2 and 6.6 Superstition Hills earthquakes. The aseismic slip at Mecca Beach in this event was 6.4 mm, significantly greater than the potential slip which accumulated between July 1986 and November 1987 if a slip rate of 2.56 mm/yr is assumed. This observation underscores the complex nature of the triggered slip phenomena and suggests that the magnitude of slip deficit and site parameters of earthquake motion both influence the size of triggered displacements.

Factors controlling the location of triggered slip. Sharp *et al.* (1986b) argued that the proximity of surficial cracks they observed to the epicenter of the North

Palm Springs earthquake indicated that a threshold value of strong ground motion was required for surface cracking. However, the large distance separating the North Palm Springs earthquake from some localities affected by the associated triggered aseismic slip suggests that other factors are involved. Acceleration reached 0.78 *g* (vertical) at North Palm Springs, about 9 km from the North Palm Springs earthquake epicenter (Porcella *et al.*, 1986). The maximum horizontal acceleration recorded at Indio, 44 km from the epicenter and adjacent to the southern Indio Hills, was 0.13 *g*. Despite large differences in maximum acceleration and distance from the main shock, the magnitude of slip in the southern Indio Hills was similar to the maximum displacement reported by Sharp *et al.* (1986b) in the epicentral area.

The presence or absence of slip deficiency along a fault may also control the location of subsequent triggered slip. Fault geometry, as well as material properties, may influence the locations at which a deficit accumulates. All three sections which slipped in 1986 and are documented in this report are within convergent segments of the fault identified by Bilham and Williams (1985). Bilham and Williams showed that, in 1979 and 1968, triggered slip occurred on two 12-km-long segments with about 7° oblique convergence. These convergent fault segments can be expected to have a higher normal stress than the intervening segments that are parallel to the slip direction (see, e.g., Segall and Pollard, 1980). Higher normal stress may increase friction and influence creep behavior toward episodic rather than stable aseismic slip mechanisms, thus allowing a slip deficit to accumulate between creep events. Ground shaking during the North Palm Springs earthquake may have caused momentary reduction of the normal stress, thus allowing the fault to slip. Slip-parallel segments have not been shown to experience either steady-state or episodic aseismic slip. However, instrumentation required for the detection of displacements along the slip-parallel segments is limited to an alignment array and creepmeter at North Shore, a community between Mecca Beach and the Mecca Hills. Additional alignment array installations within the slip-parallel segments could resolve whether aseismic slip is present along all segments of the southern San Andreas fault.

Depth of the slipping zone. Some evidence exists that the slipping zone of the fault is quite shallow. Goulty and Gilman (1978) modeled creep on a 30- to 510-m-deep patch of the San Andreas fault in Cholame Valley utilizing records of strain measured along a baseline 210 to 2200 m from the fault. Three of the four strain events observed by them were followed 1 week later by aseismic displacement at the surface. Sharp *et al.* (1986a) utilized leveling data and an elastic model to propose a maximum depth of vertical displacement on the Imperial fault of <100 m after the 1981 Westmorland earthquake (M_L 5.6). We have modeled the tilt observed during the second creep event as the response to a dislocation in an elastic half-space. Although a unique solution is not possible, all of the possible solutions with reasonable fault geometries constrain the depth of slip during the second creep event to within 120 m of the surface. In this analysis, fault geometries that were considered reasonable had depth/length ratios of 10 or less. If the fault geometries are limited to those with depth/length ratios of 1 or less, then slip is constrained to lie within less than 15 m of the surface. Any creep below this depth must occur gradually, in small enough increments so as not to produce observable tilt at the surface. Even if the slip is shallow, it may be driven by elastic loading of the crust at seismogenic depths. Louie *et al.* (1985) attribute aseismic slip in southern California to the accumulation of seismic dislocations away from slipping faults, or to deep aseismic motion which is expressed as seismicity in one area and aseismic slip in another.

Steady-state versus accelerating slip. If aseismic slip is confined to very shallow depths, it may represent steady-state behavior and not incipient seismic fault rupture. Alternatively, creep may express weakening of the fault prior to seismic failure. If the creep rate is changing, triggered aseismic slip and simple creep could express a mature stage in the earthquake cycle. Better determinations of historical and young prehistoric offsets, together with continued slip monitoring by creepmeter and geodetic methods, will be required to resolve this question.

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