Bulletin of the Seismological Society of America, Vol. 79, No. 2, pp. 362–375, April 1989

SLIP ON THE SUPERSTITION HILLS FAULT AND ON NEARBY FAULTS ASSOCIATED WITH THE 24 NOVEMBER 1987 ELMORE RANCH AND SUPERSTITION HILLS EARTHQUAKES, SOUTHERN CALIFORNIA

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ABSTRACT

Alignment arrays and creepmeters spanning several faults in southern California recorded slip associated with the 24 November 1987 Elmore Ranch and Superstition Hills earthquakes. No precursory slip had occurred on the Superstition Hills fault up to 27 October 1987, when the last measurement before the earthquakes was made. About 23 days before the earthquake, dextral creep events of about 13 mm and 0.5 mm may have occurred simultaneously on the Imperial and southern San Andreas faults, respectively, but the tectonic origin of the smaller event is questionable.

Within 12 hr after the Superstition Hills earthquake, 20.9 cm of dextral slip occurred on the main fault trace at the Superstition Hills alignment array, and 39.8 cm of dextral slip was recorded over the entire 110-m width of the array. Despite this initial wide distribution of slip, nearly all of the postseismic slip is occurring on the main fault trace. As of 3 August 1988, the alignment array had recorded a total of 80.2 cm of dextral slip. As of 5 days after the earthquakes, 65 to 80 per cent of the total slip measured by the alignment array had occurred on discrete, mappable fractures.

In addition, the two earthquakes triggered slip on the Coyote Creek fault, the southern San Andreas fault, and on the Imperial fault. Telemetered data from creepmeters on the southern San Andreas and Imperial faults indicate that triggered slip began there within 3 min or less of each of the two earthquakes. Additional triggered slip occurred on the Imperial fault beginning 3.5 hr after the second earthquake.

INTRODUCTION

At 0153 UT on 24 November 1987, the M_s 6.2 Elmore Ranch earthquake occurred and was associated with ruptures on a complex set of faults, located just northeast of the Superstition Hills fault. The maximum surface displacement associated with this earthquake was 12.5 to 13 cm left lateral, on the northeast-trending Elmore Ranch fault (Budding and Sharp, 1988; Hudnut *et al.*, 1989). About 11 hr later, at 1316 UT on 24 November 1987 the Superstition Hills fault and two related faults to the south ruptured, producing the M_s 6.6 Superstition Hills earthquake (Budding and Sharp, 1988; Williams and Magistrale, 1989).

These two earthquakes are of interest not only in and of themselves, but also because of their implications for future seismic activity in the Salton trough. Historically, the active, right-lateral, strike-slip faults of the Salton trough (Fig. 1) have displayed similar behavior in many respects. For example, the Coyote Creek fault, the Imperial fault, the Superstition Hills fault, and the southern San Andreas fault have all exhibited aseismic creep as well as slip triggered by other moderate earthquakes in the region (Allen *et al.*, 1972; Fuis, 1982; Sieh, 1982; Louie *et al.*, 1985; Sharp *et al.*, 1986a, b; Williams *et al.*, 1988). With the occurrence of the 24 November 1987 Superstition Hills earthquake, three of these four faults have now

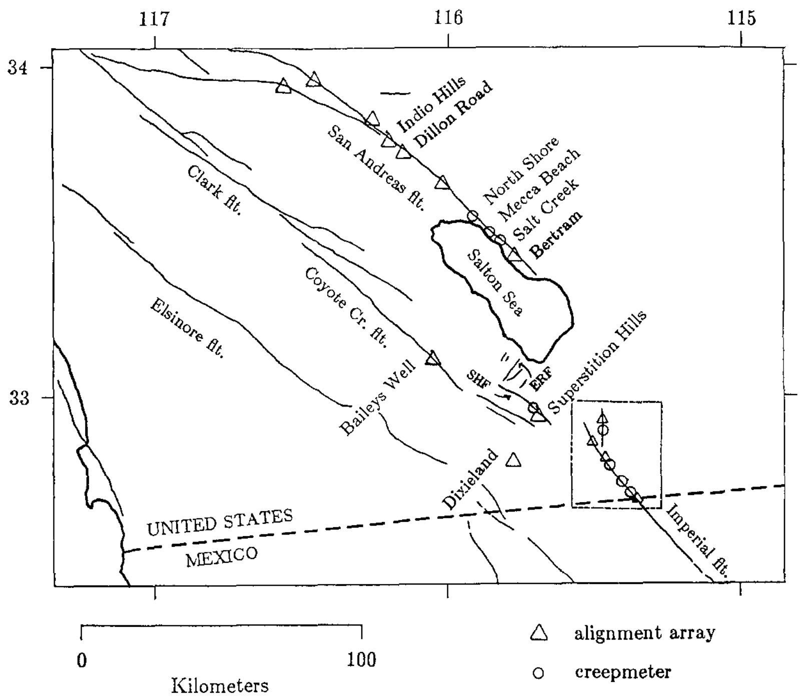

FIG. 1. Locations of Caltech alignment arrays and creepmeters spanning major faults in southernmost California. Labeled stations are those discussed in the text. Stations within the dashed box are shown in Figure 7. Abbreviations: SHF, Superstition Hills fault; ERF, Elmore Ranch fault, generalized, from Hudnut *et al.* (1989).

also ruptured seismically in the historical period, leaving us to wonder when the southern San Andreas fault will follow suit.

Under contract to the USGS, Caltech maintains a number of theodolite alignment arrays and creepmeters spanning several faults in southern California. Many of these arrays and instruments recorded slip associated with the Elmore Ranch and Superstition Hills earthquakes. These data constrain the timing and location of any possible precursory activity, record the amounts and distributions of co-seismic and postseismic slip on the Superstition Hills fault and record the location and timing of slip on other faults that was triggered by the two earthquakes.

HISTORY OF SLIP ON THE SUPERSTITION HILLS FAULT

Minor right-lateral displacement was first observed across the Superstition Hills fault following the M_L 5.6 earthquake of 23 January 1951, which occurred on or near the Superstition Hills fault (Allen *et al.*, 1965). On 1 January 1966, cracks were again observed along the Superstition Hills fault by C. R. Allen and J. N. Brune. In response to this observation, a theodolite alignment array was established across the fault just north of Imler Road on 11 May 1967. The geometry of the alignment array is shown in Figure 2. Slip is assumed to be parallel to the fault zone and is calculated from the changes in the angles between pairs of targets on opposite sides of the fault. (See Louie *et al.* (1985) for a more detailed description of the Caltech alignment arrays.)

The data from the Superstition Hills alignment array for the 20.5 years prior to the 1987 earthquakes are shown in Figure 3. The alignment array recorded about 18 ± 12 mm of dextral slip triggered by the 1968 Borrego Mountain earthquake,

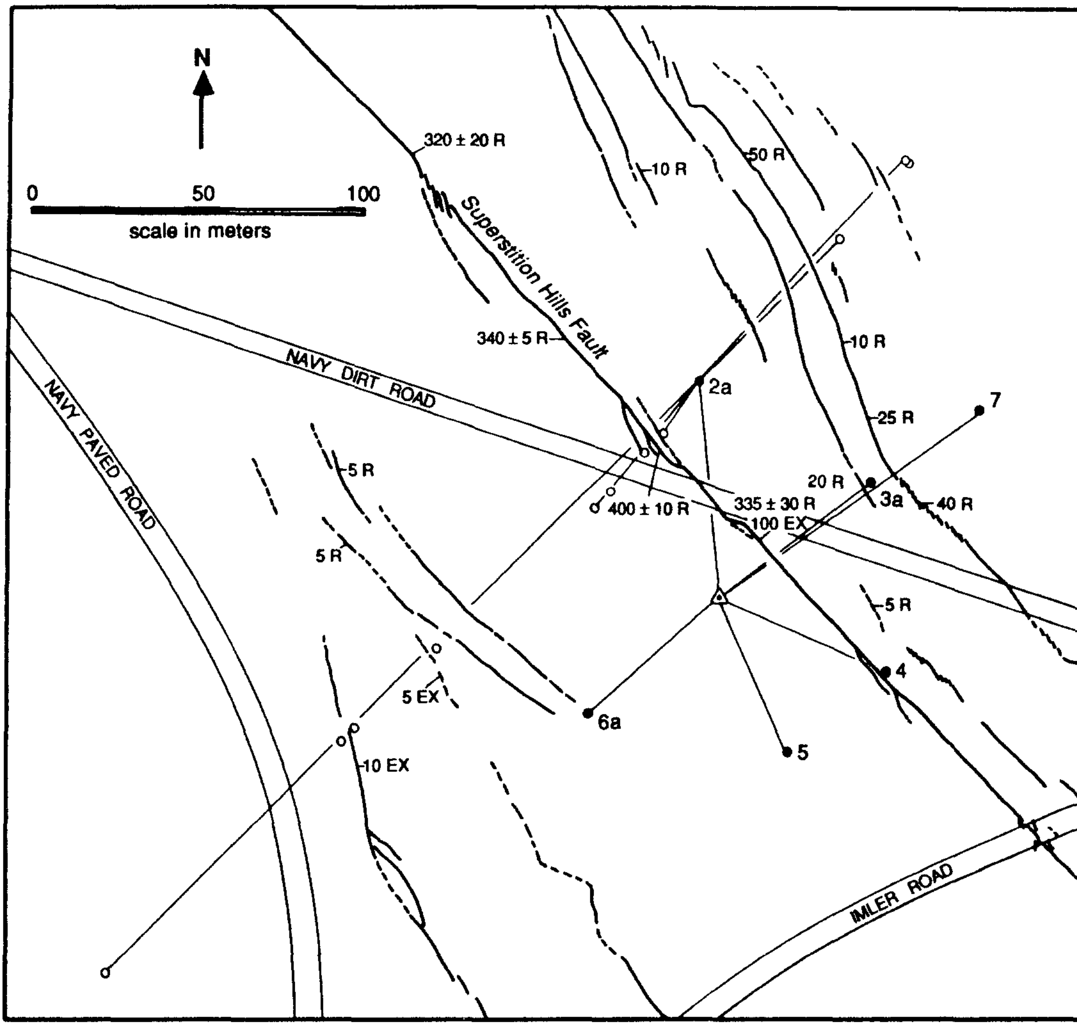

FIG. 2. Map showing surface fractures on the Superstition Hills fault in the vicinity of the Caltech alignment array. Displacements shown are in millimeters and were measured by K. Hudnut on 29 November 1987, 5 days after the Superstition Hills earthquake. The conventions used are: R = right lateral displacement, EX = extensional displacement. The Caltech alignment array is centered at the triangle. Targets surveyed from this instrument site are shown as black dots labeled 2a, 3a, 4, 5, 6a, and 7. A supplementary alignment array, established after the earthquake, is centered on Caltech target 2a, from which targets at the open circles were surveyed.

where the error given is twice the standard deviation of the slip calculated from different target pairs. Allen *et al.* (1972) measured 15 mm of right-lateral displacement on surface cracks near the alignment array, confirming the value recorded by the alignment array. After 1968, the alignment array did not record any additional resolvable slip until the November 1987 earthquakes. Although about 6 mm of dextral slip is suggested by the alignment array data from the two resurveys spanning the time of the 1979 Imperial Valley earthquake (Fig. 3 and Fuis, 1982, Fig. 115), this is probably not significant because only one target pair existed at this time, and because the data contain many fluctuations of this size. The 1979 event did trigger slip along much of the Superstition Hills fault, but surface cracking did not occur within 1 km of the alignment array (Fuis, 1982, plate 2).

In May 1968, a creepmeter was installed across the Superstition Hills fault, 3.2

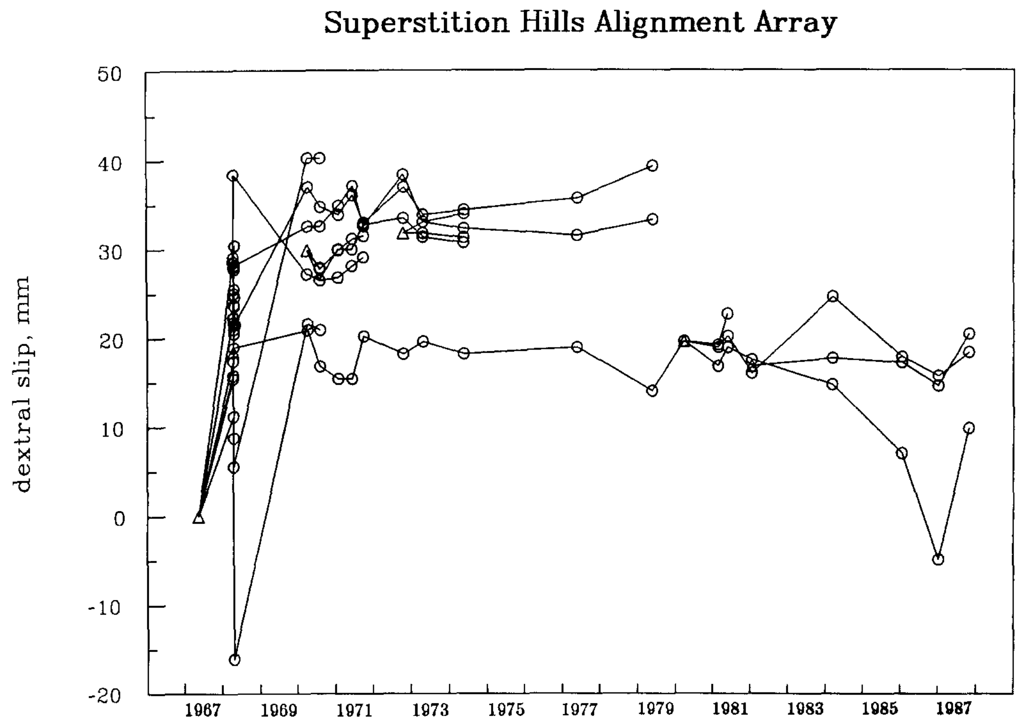

FIG. 3. Data from the alignment array spanning the Superstition Hills fault. Each circle represents the slip as measured by one pair of targets on opposite sides of the fault. Triangles mark the initial survey and indicate where values were assumed for new targets, based on measurements of existing targets.

km northwest of the alignment array. For the following 11 yr the creepmeter recorded right-lateral, aseismic creep at the rate of 0.5 mm/yr. In October 1979 it recorded 11 mm of right-lateral slip triggered by the Imperial Valley earthquake (Louie *et al.*, 1985). Fuis (1982) measured 6 to 7 mm of dextral slip on surface cracks nearby. Since that time the creepmeter recorded no slip up to 27 October 1987, when the last measurement before the earthquakes was made. However, Sharp *et al.* (1986a) reported slip nearby on the Superstition Hills fault that was triggered by the 1981 Westmorland earthquake.

CONSTRAINTS ON POSSIBLE PRECURSORY ACTIVITY

Neither the creepmeter nor the alignment array recorded any precursory slip on the Superstition Hills fault up to 27 October 1987, 1 month before the earthquakes. Our data do not constrain whether or not any precursory slip occurred after that time. However, Jim Kahle of the CDMG visited the Superstition Hills fault at Imler Road after the Elmore Ranch earthquake and 2.75 hr before the Superstition Hills earthquake. He observed no fresh cracks at that time (Kahle *et al.*, 1988), so it seems likely tht that no precursory slip occured up to 2.75 hr before the Superstition Hills earthquake.

Data telemetered to Pasadena via satellite from creepmeters on the southern San Andreas and Imperial faults indicate the occurrence of some enigmatic events 20 to 25 days before the earthquakes. These data suggest creep events may have occurred simultaneously at Ross Road on the Imperial fault and at Salt Creek on the southern San Andreas fault, between 31 October and 4 November 1987 (Fig. 4). These events,

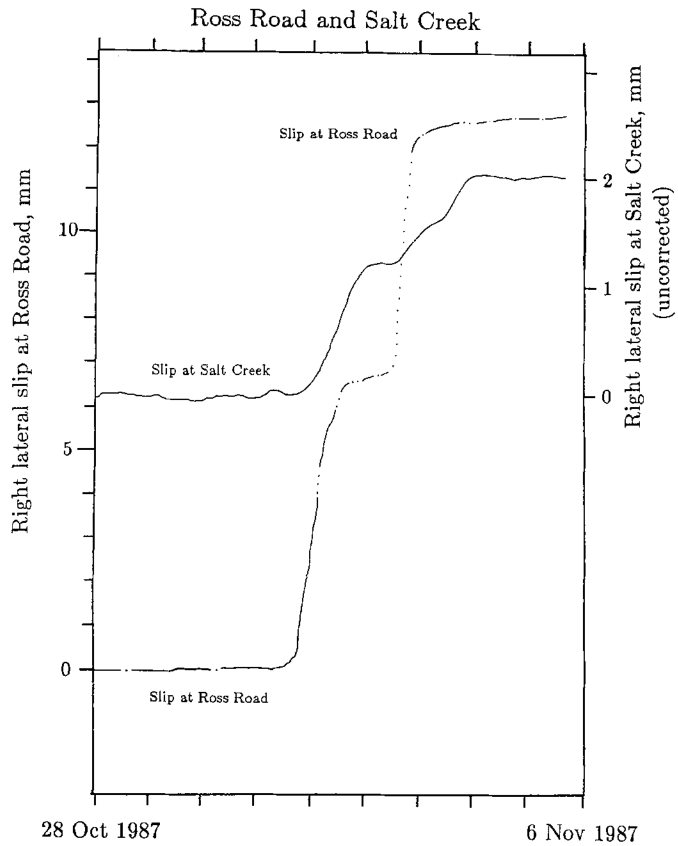

FIG. 4. Data from the creepmeters at Ross Road, on the Imperial fault, and at Salt Creek, on the southern San Andreas fault, for the period from 27 to 18 days before the 24 November 1987 earthquakes. Dots fill in gaps in the transmission of data from Ross Road. The slip at Ross Road was great enough to cause two complete revolutions of the potentiometer in that creepmeter, and uncertainties in the behavior of the potentiometer under those circumstances lead to a ±0.7 mm uncertainty in the amount of slip at Ross Road. Note that the data from Salt Creek shown in this figure have *not* been corrected for temperature effects. The data from Ross Road do not require a temperature correction (see text).

if real, would be of particular interest, because the two localities are 80 km apart and on different faults. Simultaneous creep events would suggest some sort of deep-seated strain episode of regional extent.

Unfortunately, the signal recorded by the Salt Creek creepmeter is of questionable origin, owing to the passage at that exact time of an unusually strong cold front through the region—the most intense frontal system of the entire year. Although the creepmeter recorded 2 mm of apparent right-lateral slip, this value is reduced to 0.5 mm after correcting for the effects of the temperature drop on the stainless-steel creepmeter wire, and the error in the temperature correction is sufficiently large that no slip is required by the data. The same cold front passed through the region of the Ross Road creepmeter, but that instrument utilizes invar wire of very low temperature-sensitivity. Furthermore, the calculated slip of 12.1 to 13.4 mm at Ross Road is considerably greater than that suggested by the signal at Salt Creek—much too large to be associated with the abrupt temperature change, or the accompanying heavy rainfall.

Thus, despite the intriguing temporal correlation between the two signals, as well as their strikingly similar double-event shapes (Fig. 4), we are left with a high degree of uncertainty as to whether a regional strain episode occurred precursory to the 24 November 1987 earthquakes. Supporting this uncertainty is the absence of a detectable strain event at that time at the 100-km-distant UCSD Piñon Flat Observatory (Duncan Agnew, personal comm.). Clearly, however, a significant slip event did occur at Ross Road, on the Imperial fault, 20 to 25 days before the 24 November 1987 earthquakes, which were centered some 40 km away.

Co-Seismic and Postseismic Slip on the Superstition Hills Fault

Observations

Figure 5 shows the data from the alignment array on the Superstition Hills fault, beginning with the last resurvey prior to the two earthquakes. These data are also listed in numerical form in Table 1. The first resurvey after the earthquakes was done about 12 hr after the Superstition Hills earthquake. At that time, the alignment array recorded slip ranging from 20.9 cm for targets near the fault to 39.8 cm for targets farther from the fault. As is shown in Figure 2, this 18.9-cm-wide range in slip values is partially due to the fact that targets farther from the fault also measured displacement across secondary fault traces and discontinuous fractures, in addition to the slip on the main fault trace. The percentage of this distributed shear that did not occur on mappable fractures will be discussed later.

In contrast, after the first 12 hr, all of the alignment array targets measured the

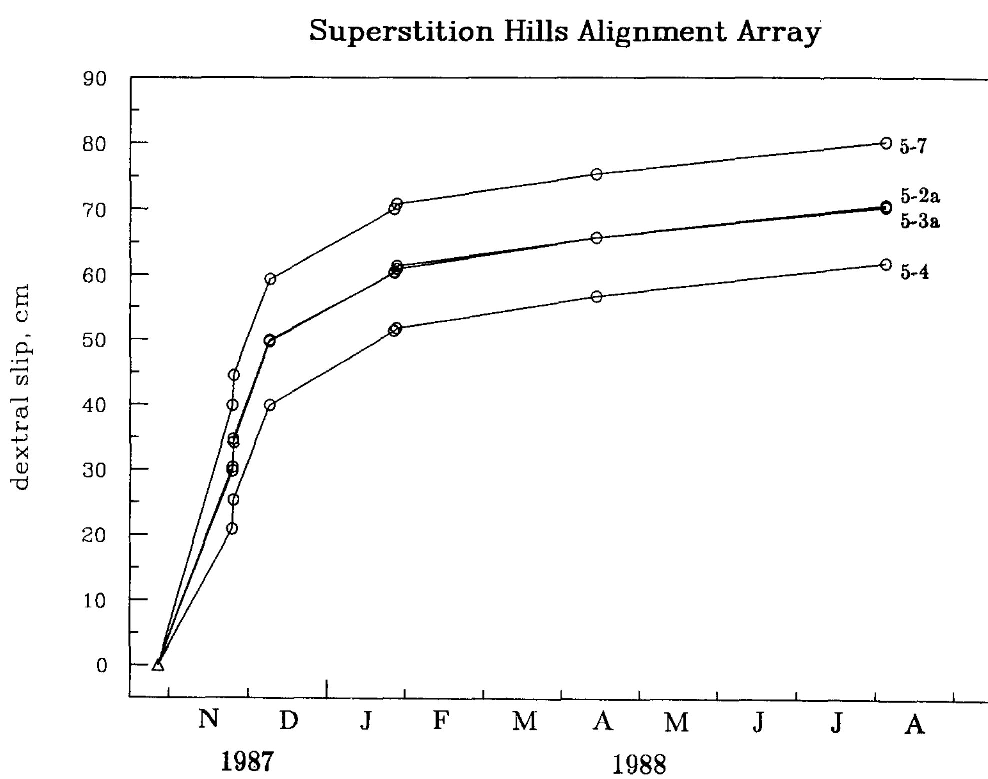

FIG. 5. Data from four target pairs (5-2a, 5-3a, 5-4 and 5-7) within the Superstition Hills alignment array, beginning with the last resurvey before the 24 November 1987 earthquakes. Data from target pairs including target 6a are not plotted because target 6a may have been disturbed between 27 October and 24 November 1987. See Figure 2 for the locations of alignment array targets. The sharp increase in slip that occurred between 27 and 28 January 1988 was associated with a M_L 4.8 aftershock.

same amount of postseismic slip (Fig. 5), suggesting that all of the postseismic slip is occurring on the main fault trace. Consistent with this, 1- to 2-m-aperture arrays established across many of the secondary fault traces in February 1988 have not recorded any postseismic slip. The latest resurvey of the alignment array was done on 3 August 1988. At that time, the total co-seismic and postseismic slip measured by the array was 80.2 cm. Although none of the target pairs spans the whole fault zone (Fig. 2), the slip on the outermost fractures is minor, so the alignment array measurements probably do not significantly underestimate the total slip.

The data for each target pair in the alignment array can be fit equally well by a logarithmic function (slip = $a + b$ log(time), where a and b are constants) and by a power-law function (log(slip) = $c + d$ log(time), where c and d are constants) (Table 2). The correlation coefficients are 0.997 to 0.998 for the logarithmic function and 0.998 to 0.999 for the power-law function. The average absolute value of residuals is 0.75 cm and 0.80 cm, respectively. Extrapolation of the best-fitting logarithmic function to 10 yr after the time of the Superstition Hills earthquake predicts 96.5 cm of dextral slip between targets 5 and 7 at that time, while extrapolation of the best-fitting power-law function predicts that 109.5 cm of dextral slip will occur between targets 5 and 7 within 10 yr after the earthquake.

Comparison of Alignment Array Data with Slip on Surface Fractures

The amount of slip that occurred across each of the surface fractures was measured by K. Hudnut 5 days after the Superstition Hills earthquake (Fig. 2). Although the surface faulting pattern was particularly complex in the vicinity of the alignment array, and the amount of surface slip on each of the traces varied along strike, it appears that 35.0 to 42.5 cm of dextral slip occurred on surface fractures between

TABLE 1
DATA FROM THE CALTECH ALIGNMENT ARRAY

Date	Time (PST)	Dextral Slip (cm)			
		5-4	5-2a	5-3a	5-7
10/27/87	3:43 pm	0.0	0.0	0.0	0.0
11/24/87	4:55 pm	20.94	29.86	30.41	39.85
11/25/87	11:10 am	25.34	34.17	34.77	44.48
12/09/87	9:25 am	39.94	49.73	49.94	59.34
01/27/88	10:00 am	51.32	60.44	60.32	70.04
01/28/88	10:12 am	51.74	61.33	60.89	70.79
04/13/88	6:00 pm	56.69	65.68	65.66	75.36
08/03/88	6:22 pm	61.79	70.62	70.30	80.22

TABLE 2
PARAMETERS FOR BEST-FIT FUNCTIONS TO THE CALTECH ALIGNMENT ARRAY DATA

		5-4	5-2a	5-3a	5-7
logarithmic function	a	3.7062	12.6937	13.7664	23.0557
slip(cm) = a + blog[time(hrs after eq)]	b	14.9989	15.0605	14.7165	14.8325
	r	0.9970	0.9980	0.9982	0.9980
	ρ	0.82	0.78	0.68	0.73
power-law function	c	1.1458	1.3313	1.3437	1.4844
log[slip(cm)] = c + dlog[time(hrs after eq)]	d	0.1742	0.1395	0.1355	0.1123
	r	0.9984	0.9985	0.9989	0.9994
	ρ	0.97	0.90	0.77	0.54

r = correlation coefficient; ρ = average of absolute values of residuals (cm).

targets 5 and 7 of the alignment array. The sum of the slip on these surface cracks accounts for only 65 to 80 per cent of the slip (about 54 cm) that would have been measured by target pair 5-7 of the alignment array at that time, based on an interpolation between alignment array measurements using the best-fitting logarithmic functions. As time goes on this percentage will presumably increase, because nearly all of the postseismic slip is occurring on a mappable fracture, namely the main fault trace.

Movement that Did Not Occur on Mappable Surface Fractures

As noted earlier, the alignment array recorded 18.9 cm of dextral shear northeast of the main fault trace within 12 hr after the Superstition Hills earthquake (Fig. 5). Of this, only about 4.5 to 6.0 cm occurred as slip on mapped fractures northeast of the main fault trace (Fig. 2). The remaining 12.9 to 14.4 cm of movement may have occurred as slip on numerous fractures too small to cause detectable surface cracking, or as an elastic response to increasing co-seismic slip with depth on the main fault trace.

If the latter explanation is correct, one might expect postseismic slip to occur at shallow depths, thus equalizing the depth distribution of total slip on the fault and relaxing any elastic strain that had occurred due to greater co-seismic slip at depth. If this is the case, the postseismic alignment array data should show greater movement for target pairs nearer to the fault than for those farther from the fault. However, as mentioned earlier, all target pairs recorded the same amount of postseismic slip, to within ± 0.8 cm (2σ).

A supplementary alignment array was established on 5 March 1988. It extended coverage 150 m southwest and 30 m northeast of the Caltech alignment array (Fig. 2). This supplementary array *did* record greater postseismic movement for targets near the fault than for those farther from the fault (Fig. 6). This decrease in movement with distance from the fault primarily occurred at distances greater than 75 m southwest of the fault, outside the region covered by the Caltech alignment array. Thus, some elastic strain probably occurred co-seismically at distances greater than 75 m from the fault and then relaxed postseismically. However, the data from the supplementary array are consistent with the data from the Caltech alignment array, which indicate that if any elastic strain occurred co-seismically within 75 m of the fault, it has not relaxed within the first 8 months after the earthquake. Thus, the 12.9 to 14.4 cm of dextral movement that was recorded by the alignment array, but did not occur on mappable fractures, probably did not occur elastically, and is more likely due to slip on a pervasive set of minute fractures.

Slip Triggered on Other Faults

Observations

The 24 November 1987 earthquakes triggered minor slip on the Coyote Creek fault, the southern San Andreas fault, and the Imperial fault. Table 3 summarizes the observations of triggered slip at Caltech alignment arrays and creepmeters. In the table, the errors given for alignment array data are twice the standard deviation of the slip calculated from different target pairs. The locations of alignment arrays and creepmeters on the Imperial and Brawley faults are shown in Figure 7.

The data from the Salt Creek creepmeter on the southern San Andreas fault and from the Ross Road creepmeter on the Imperial fault are sampled every 3 min and are telemetered to Caltech daily via satellite. The data from these creepmeters

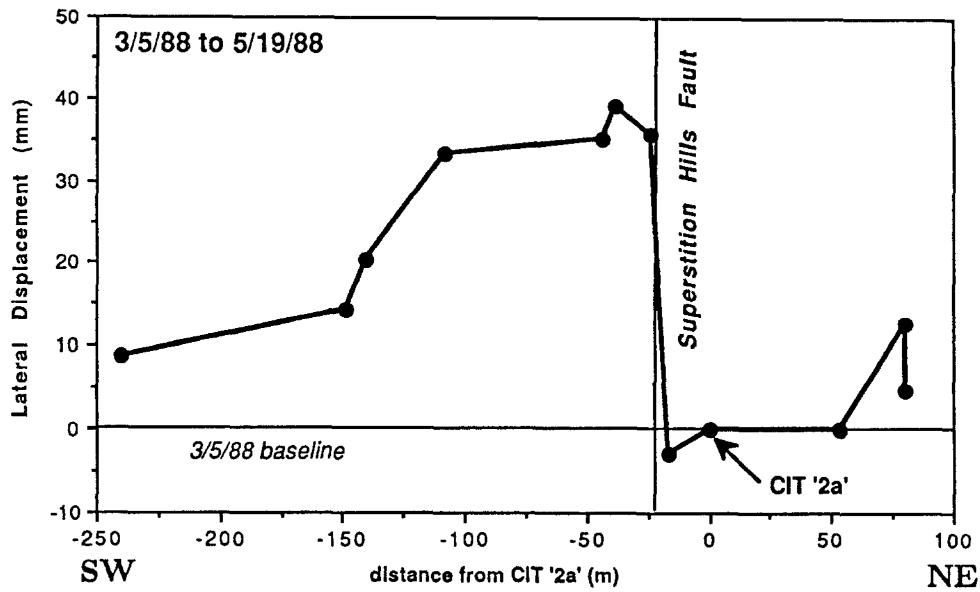

FIG. 6. Data from the supplementary alignment array, for the period 5 March to 19 May 1988. Lateral displacements were calculated from measured angles and distances. The data southwest of the fault clearly show less right-lateral displacement with increasing distance from the fault, especially at distances greater than 75 m from the fault. Measurements were made with a Zeiss Elta-4 instrument, with an angular precision of ±15 μrad, so maximum instrumental error is about ±4 mm. The earlier survey is shown as a zero-displacement line. The segment from Caltech target 2a to the next target northeast was assumed to have no displacement between surveys, thus the displacements are relative to that 50-meter line. Target locations are shown in Figure 2.

before, during, and after the 1987 earthquakes are shown in Figure 8. Both creepmeters recorded slip events within 3 min or less of the time of each earthquake, possibly at the arrival time of the seismic waves at the creepmeters. The precise time constraints on the nearly co-seismic, triggered-slip events are given in Table 3 and were calculated based on the earthquake origin times reported by Magistrale *et al.* (1989).

The Ross Road creepmeter also recorded an additional 6.9 to 7.6 mm of slip that began 3.5 hr after the second earthquake (Table 3, Fig. 8b). This slip probably occurred in two creep events. Data are available for the first 4.4 to 5.1 mm of slip that occurred, but after that there is a 3-day gap in the data, due to a misunderstanding about scheduling of the data retrieval over the Thanksgiving weekend. The last data before the gap record a diminishing slip velocity that is too small to account for the additional 2.5 mm of dextral slip that occurred before the end of the data gap. Thus the slip velocity must have increased again in another creep event during the time of the data gap.

Triggering Mechanism

These data allow further evaluation of the proposed mechanisms for triggered slip. Sharp *et al.* (1986b) and Allen *et al.* (1972) suggested that, on creeping faults, surface creep may lag behind movement at depth, producing a slip deficit near the surface. The strong shaking caused by an earthquake may then trigger the release of this accumulated, near-surface slip. Although we regard this as a good working model, our data suggest that the factors controlling the release of such slip are quite complex.

TABLE 3

OBSERVATIONS OF SLIP TRIGGERED BY THE 24 NOVEMBER 1987 EARTHQUAKES

Fault	Site	Dextral Slip (mm)	Period in which slip occurred or initiated
Southern San Andreas fault	Indio Hills alignment array	no slip (2 ± 12)	30 Oct 1987–4 Aug 1988
	Dillon Road alignment array	no slip	30 Oct 1987–4 Aug 1988 (−1 ± 5)
	North Shore creepmeter	no slip (−1 ± 2)	29 Oct–22:15 UT 24 Nov 1987
	Mecca Beach creepmeter	6.4	28 Sept–22:43 UT 24 Nov 1987
	Salt Creek creepmeter	1.3	began 2 min before to 1 min after Elmore Ranch earthquake
		1.7	began 12 sec to 3.2 min after Superstition Hills earthquake
	Bertram alignment array	no slip (8 ± 44)	28 Oct 1987–4 Aug 1988
Coyote Creek fault	Bailey's Well alignment array	21 ± 20	28 Oct–16 Dec 1987
Unnamed fault	Dixieland alignment array	no slip (−3 ± 11)	10 Dec 1985–3 Aug 1988
Brawley fault	Harris Road creepmeter	no slip (0.4 ± 2)	27 Oct 1987–13 Apr 1988
Imperial fault	Worthington Rd alignment array	25 ± 14	9 July–17 Dec 1987
	Highway 80 alignment array	21 ± 4	27 Oct–17 Dec 1987
	Ross Road creepmeter	0.2	began 2.25 min before to 0.75 min after Elmore Ranch earthquake
		0.2	began 0 to 3 min after Superstition Hills earthquake
		6.9–7.6	began 3.5 hr after Superstition Hills earthquake
	Heber Road creepmeter	8.2	15 Oct–25 Nov 1987
	Tuttle Ranch creepmeter	no slip (−0.4 ± 1)	15 Oct–25 Nov 1987

For example, the data from Salt Creek (Fig. 8a, Table 3) indicate that a creep event occurred very shortly after each of the triggering earthquakes, perhaps at the arrival time of the seismic waves at Salt Creek. If the first earthquake had completely released the accumulated, near-surface slip at Salt Creek, then one would not expect the second earthquake, only 11.4 hr later, to have triggered a second, and slightly larger, creep event at Salt Creek. The occurrence of the second creep event may indicate that if the slip-deficit model is correct, the entire accumulated slip need not be released in any single triggered-slip event. Other factors, such as the magnitude, directivity, and duration of local shaking, may influence how much of the accumulated slip is released.

Records from the USGS strong-motion instrument at Coachella Canal station 3,

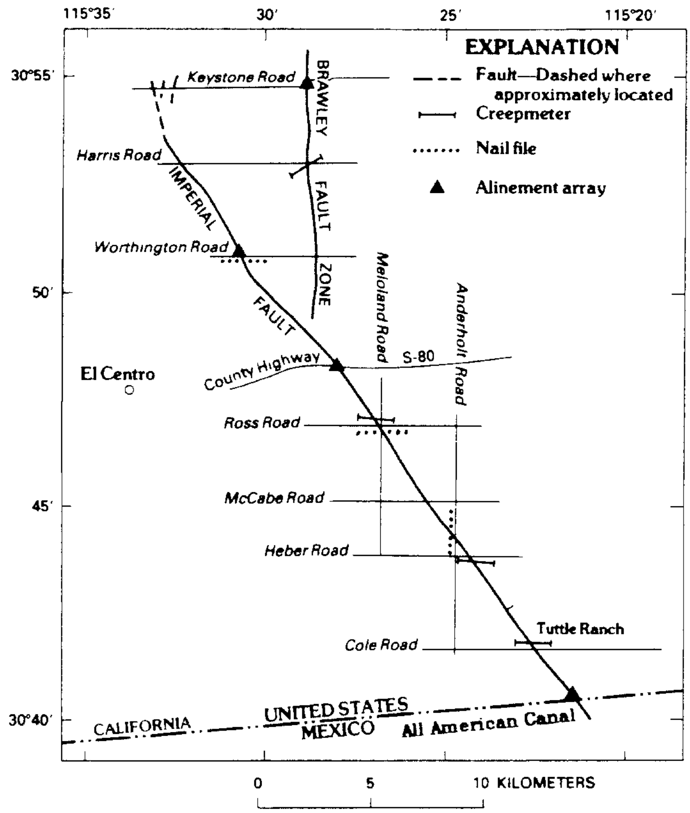

FIG. 7. Locations of Caltech alignment arrays and creepmeters on the Imperial and Brawley faults, in the Imperial Valley, California (from Cohn *et al.*, 1982).

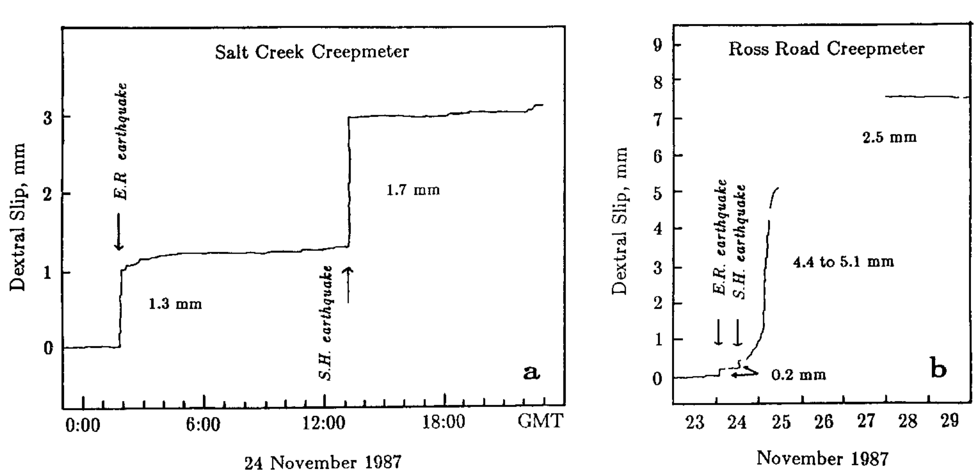

FIG. 8. Data from the Salt Creek creepmeter (a) on the southern San Andreas fault, and from the Ross Road creepmeter (b) on the Imperial fault, showing slip events triggered by the 24 November 1987 earthquakes. Arrows mark the times of the Superstition Hills and Elmore Ranch earthquakes. The range of possible slip values for the 4.4- to 5.1-mm event at Ross Road is due to uncertainties in the behavior of the potentiometer, which made a complete revolution during this event.

located 10 km northeast of the Salt Creek creepmeter, indicate that peak horizontal accelerations during the second earthquake were twice as large as those during the first at this site (Porcella *et al.*, 1987). The peak vertical acceleration during the second earthquake was also slightly larger than the peak vertical acceleration during the first earthquake, and the duration of strong shaking was longer in the second earthquake (Porcella *et al.*, 1987). Thus the larger amount of slip in the second triggered creep event at Salt Creek may be due to the stronger accelerations and longer duration of shaking in the second earthquake.

The strong-motion data from the El Centro array (Porcella *et al.*, 1987), near the Ross Road creepmeter, also indicate that the accelerations and duration of strong shaking were greater there in the second earthquake than in the first. However, the two essentially co-seismic creep events at Ross Road had the same amount of slip, and the second delayed creep event involved a *smaller* amount of slip (2.5 mm) than did the first one (4.4 to 5.1 mm). Thus, at this location the duration and magnitude of local shaking did not correlate well with the amount of slip triggered by a given earthquake.

Co-seismic and Delayed Triggered-Slip Events

The creepmeters at Ross Road and Salt Creek recorded some triggered-slip events essentially co-seismically, but the Ross Road creepmeter also recorded slip events hours after the triggering earthquakes. It may be that the co-seismic events and the delayed events originated at different depths, or at different distances from the creepmeters. The triggered-creep events that were recorded within minutes after the two earthquakes likely originated at or very near the surface, because they affected the creepmeters almost immediately. The 4.4- to 5.1-mm creep event at Ross Road, however, was not recorded by that creepmeter until 3.5 hr after the second earthquake and 15 hr after the first earthquake. It may be that this 4.4- to 5.1-mm slip event originated at depth, and/or at some distance along the strike of the fault, during the shaking caused by one of the two earthquakes, and that it then propagated to the creepmeter during the following hours. The later, 2.5-mm triggered-slip event at Ross Road (the event that occurred during the gap in the data in Fig. 8b) may also have begun at depth or at some distance from the creepmeter during the shaking caused by one of the earthquakes.

Triggered-slip events that do not reach the surface until hours or days after the triggering event have been observed several times in the past (Allen *et al.*, 1972, p. 102; Sieh, 1982; Williams *et al.*, 1988). Using measurements from a creepmeter and a tiltmeter, Williams *et al.*, (1988) showed that a triggered-creep event recorded by a creepmeter at Mecca Beach 33 hr after the 8 July 1986 North Palm Springs earthquake, originated at depth or elsewhere along the fault within minutes after the time of the earthquake. Therefore, it is reasonable to suggest that the 4.4- to 5.1-mm event and the 2.5-mm event at Ross Road began at depth or away from the creepmeter during the shaking produced by one or both of the November 1987 earthquakes, and that they propagated to the creepmeter during the following hours.

It is also interesting to note the differences in the form of the shallow, essentially co-seismic, triggered-slip events and the delayed events. The events that were recorded almost co-seismically had short durations ($\leqq 4$ min for the events triggered by the Elmore Ranch earthquake, and $\leqq 3$ min for the events triggered by the Superstition Hills earthquake), and rapid slip velocities ($\geqq 5.4$ μm/sec and $\geqq 10$ μm/sec for the first and second creep events triggered by the Elmore Ranch earthquake, respectively, and $\geqq 0.5$ μm/sec and $\geqq 1.2$ μm/sec) for the first and second creep events triggered by the Superstition Hills earthquake). They began and ended abruptly, at the resolution at which we observed them. The delayed, 4.4- to 5.1-mm event on the other hand, had a much longer duration (>18 hr), and a maximum slip velocity (0.7 μm/sec) that is lower than the minimum slip velocities for most of the events that occurred essentially co-seismically. This event also had a more gradual beginning and end.

It may be that when first initiated the 4.4- to 5.1-mm event at Ross Road had the same characteristics as the triggered events that were recorded almost co-seismically. As it propagated to the creepmeter the slip velocity of the event may have decreased, thus increasing the duration of the event and making its beginning and end less abrupt.

Triggered Slip in Relation to the Earthquake Cycle

Apparently, triggered slip may occur at any stage in the earthquake cycle. Triggered slip occurred on the Superstition Hills fault 19 yr (Allen *et al.*, 1972), 8 yr (Fuis, 1982), and 6 yr (Sharp *et al.*, 1986a) before seismic rupture of the fault. Triggered slip occurred on the Imperial fault 11 yr before seismic rupture of that fault (Allen *et al.*, 1972), but it also occurred 2 yr (Sharp *et al.*, 1986a) and 8 yr (this paper) *after* seismic rupture of the fault. Triggered slip occurred on the Coyote Creek fault 19 yr (this paper; Hudnut and Clark, 1989) after seismic rupture of that fault. The occurrence of triggered slip thus seems to be a long-term behavioral style of certain faults and does not necessarily indicate a mature stage of the earthquake cycle.

Conclusions

During the past 21 yr, the Superstition Hills fault has experienced a history of aseismic creep, triggered slip, and now seismic rupture and postseismic slip. No conclusive evidence was found for precursory slip on the Superstition Hills fault, or for a regional strain event precursory to the Elmore Ranch and Superstition Hills earthquakes. Data from the alignment array on the Superstition Hills fault indicate that within the first 12 hr after the Superstition Hills earthquake, dextral slip was distributed over the width of the array, but since then nearly all postseismic slip has been concentrated on the main fault trace. As of 3 August 1988, 80.2 cm of right-lateral slip had occurred, and the total amount of dextral slip at the alignment array is expected to reach at least about 1 m.

A significant percentage of the dextral movement recorded at the surface by the alignment array in the first 12 hr after the Superstition Hills earthquake did not occur on mappable fractures, and probably occurred as slip on a pervasive set of minute slip surfaces. Some elastic shear strain may have been produced by increasing co-seismic slip with depth, but the relaxation of this elastic strain as postseismic slip occurred was only detectable at distances greater than 75 m from the main fault trace.

The Elmore Ranch and Superstition Hills earthquakes also triggered slip on three other faults within the region. The amount of slip triggered by each of the earthquakes cannot be simply explained by either the expected size of the near-surface slip deficit at that time or by the parameters of local strong ground motion. The record from the creepmeter at Ross Road also suggests that each of the two earthquakes triggered both minor slip at the surface and moderate slip that began at a somewhat greater depth, or at some distance along the fault. Finally, triggered slip appears to be a long-term behavioral style of certain faults, and is not specific to any particular stage in the earthquake cycle. The frequent occurrence of triggered slip on the southern San Andreas fault thus does not necessarily indicate that seismic rupture of that fault is imminent.

ACKNOWLEDGMENTS

This work was supported by USGS Grant 14-08-0001-G1177 and by funds from the Caltech Earthquake Research Associates.

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Manuscript received 15 August 1988