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NEW SLIP ALONG PARTS OF THE 1968 COYOTE CREEK FAULT RUPTURE, CALIFORNIA

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Abstract

On 28 and 30 November 1987, we found new surface ruptures along the central break of the Coyote Creek fault's 1968 rupture. Mapped slip that may have been triggered by the Superstition Hills earthquakes of 24 November 1987 was dominantly right-lateral and ranged up to 15 mm. Total length of the new ruptures was about 3 km, distributed along two quasi-continuous segments of the main fault, plus one segment of a secondary fault, all of which ruptured in 1968. The longest segment of new rupture followed the northeast side of the Ocotillo Badlands for 2.3 km. Newly mapped slip in 1987 occurred along parts of the Coyote Creek fault that were characterized in 1968 by several features. These were: large total dextral slip, a prominent vertical slip component, rupture along single fractures instead of en-echelon cracks, and large afterslip in the few years following the 1968 earthquake. Past episodes of triggered slip on the San Andreas, Imperial, and Superstition Hills faults were hypothesized by others to be precursory phenomena. The 1987 slip on the Coyote Creek fault, however, may be an episode of afterslip. This suggestion is supported by the decrease in creep rates since 1968 shown by data from two alinement arrays on the Coyote Creek fault. The correct interpretation of triggered slip events, and their value as earthquake precursors, therefore depends upon a good knowledge of the slip history of a fault.

Introduction

The Coyote Creek fault, a segment of the San Jacinto fault zone in southern California (Fig. 1), ruptured in association with the 1968 Borrego Mountain earthquake (Clark, 1972a). It had also slipped prehistorically, as Clark *et al.* (1972) documented with trenching and scarp morphology along the 1968 break. In late November 1987, the Coyote Creek fault slipped again by a small amount, apparently in response to the Superstition Hills earthquake sequence. Within the Salton trough, other faults had previously experienced similar small slip events, apparently 'triggered' by large earthquakes in the region. While a similar phenomenon may have accompanied the 1951 event near the Superstition Hills (Dibblee, 1954) and aftershocks of the 1966 Parkfield event (Scholz *et al.*, 1969), the first clear observations of this phenomenon, termed triggered slip, were associated with the 1968 earthquake. Following this event, small amounts of surface slip were mapped on the San Andreas, Superstition Hills, and Imperial faults (Allen *et al.*, 1972). In 1979, following the Imperial Valley earthquake, small amounts of slip were mapped along the San Andreas fault (Sieh, 1982) and the Superstition Hills fault (Fuis, 1982).

Because triggered slip in 1968 on the Imperial fault preceded the 1979 Imperial Valley earthquake, Sieh (1982) suggested that the phenomenon might be considered an earthquake precursor. In 1981, the Westmorland earthquake was associated with small amounts of mapped slip on the Superstition Hills fault and Imperial fault, but not on the Coyote Creek fault (Sharp *et al.*, 1986a). Considering the repetition of triggered slip events on the Superstition Hills fault, Sieh (1982) wrote that "the Superstition Hills fault . . . [may] fail seismically within the next few decades." His

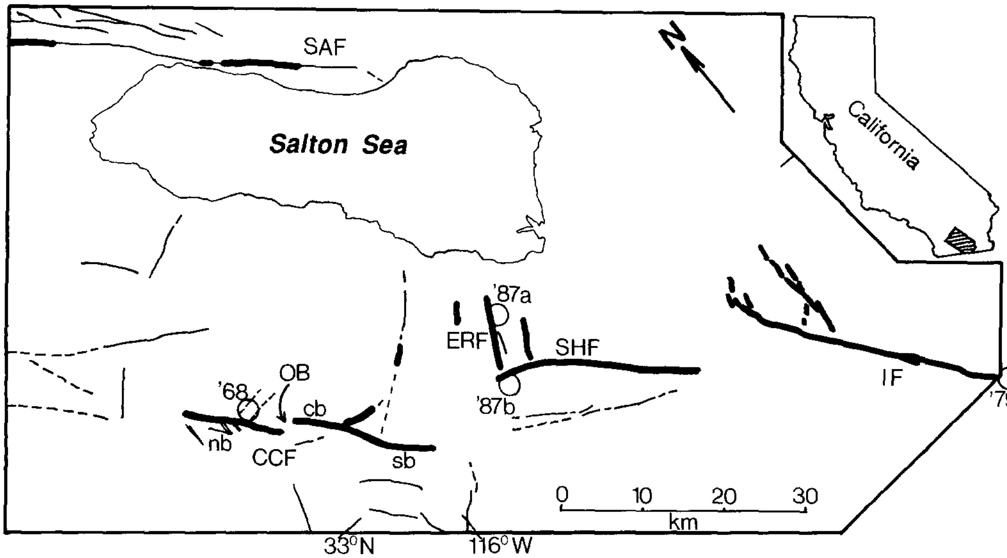


FIG. 1. Faults in the Salton trough region. Heavy traces are faults that have had surface rupture in the past two decades, either seismically or by triggered slip. This study concerns the Coyote Creek fault (CCF), parts of which ruptured in the April 1968 Borrego Mountain earthquake. We found and mapped new surface slip along this fault following the 23 to 24 November 1987 ruptures of the Elmore Ranch fault (ERF) and Superstition Hills fault (SHF). Locations of the north break (nb), central break (cb), and south break (sb), of the 1968 rupture are indicated. Other faults shown are the San Andreas fault (SAF) and Imperial fault (IF). Epicenters of the 1968, 1979, and 1987 (a and b) earthquakes are shown as circles. The Ocotillo Badlands are indicated by OB. Map compiled form Sharp (1982a) and Hudnut *et al.* (1989).

prediction was confirmed in 1987, but this success did not prove that triggered slip is a valid precursor.

Following the North Palm Springs earthquake in 1986, small amounts of mapped slip again occurred along the southern San Andreas fault (Williams *et al.*, 1988). Mappable fractures with insignificant displacements occurred near that event's epicenter (Sharp *et al.*, 1986b). The 1987 Superstition Hills earthquakes, however, failed to trigger enough slip on the San Andreas fault to produce mappable surface rupture. McGill *et al.* (1989) show, however, that several millimeters of slip were recorded on creepmeters on the San Andreas fault. The 1987 earthquakes did apparently trigger small amounts of mappable slip on the Imperial fault (Sharp, 1989) and on the Coyote Creek fault, as we document in this paper.

1987 Ruptures along the Coyote Creek Fault

New slip in 1987 along the Coyote Creek fault followed the central break of the 1968 rupture, and was confined to the section of the fault between kilometers 17.5 and 22.8 km (Fig. 2). New breaks consisted of both quasi-continuous breaks extending several meters or more and of generally <1 m long en-echelon cracks that broke the surficial crust of the desert soil. Features of these new breaks resembled photographs and verbal descriptions of small displacements on other faults in this region (Allen *et al.*, 1972).

The first observation of new slip was made at 19.05 km, at 1245 hr PST on 28 November 1987 (Fig. 2). Maximum displacements measured were 15 mm, as observed at that location and between distances of 19.40 and 19.60 km along the fault (Fig. 3). New slip was at a maximum from where the fault crosses the berm deposits of ancient Lake Cahuilla to the Bailey's Well alinement array, where an east-west

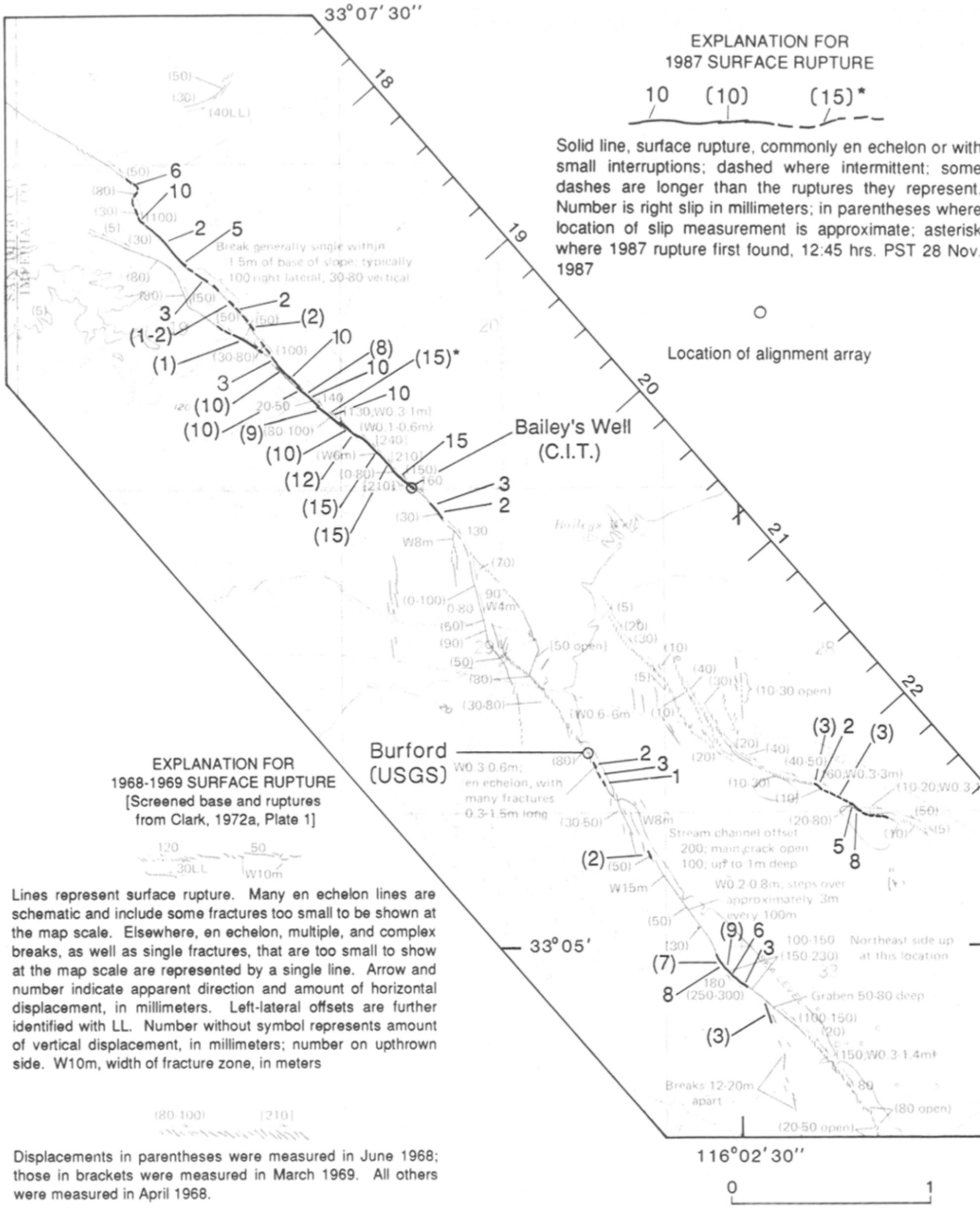


FIG. 2. Map of the new 1987 surface slip along part of the 1968 rupture of the Coyote Creek fault. Also shown are surface ruptures, slip, and afterslip data from the 1968 rupture and kilometer grid from Clark (1972a, Plate 1.1).

trending power line and dirt road cross the fault.

Near the northwest terminus of the new 1987 ruptures at about 17.5 km, the Coyote Creek fault is deflected into a minor right step of about 150 m. Both the 1968 break and the new slip in 1987 were deflected around a bend in the fault trace here, but in neither case did substantial opening occur across the fractures. In 1968, up to 50 mm of left-lateral slip was measured on northeast-trending fractures to the northeast of this location (Fig. 2). During our mapping, we noticed that this step in the Coyote Creek fault main trace coincides with the intersection of an east-

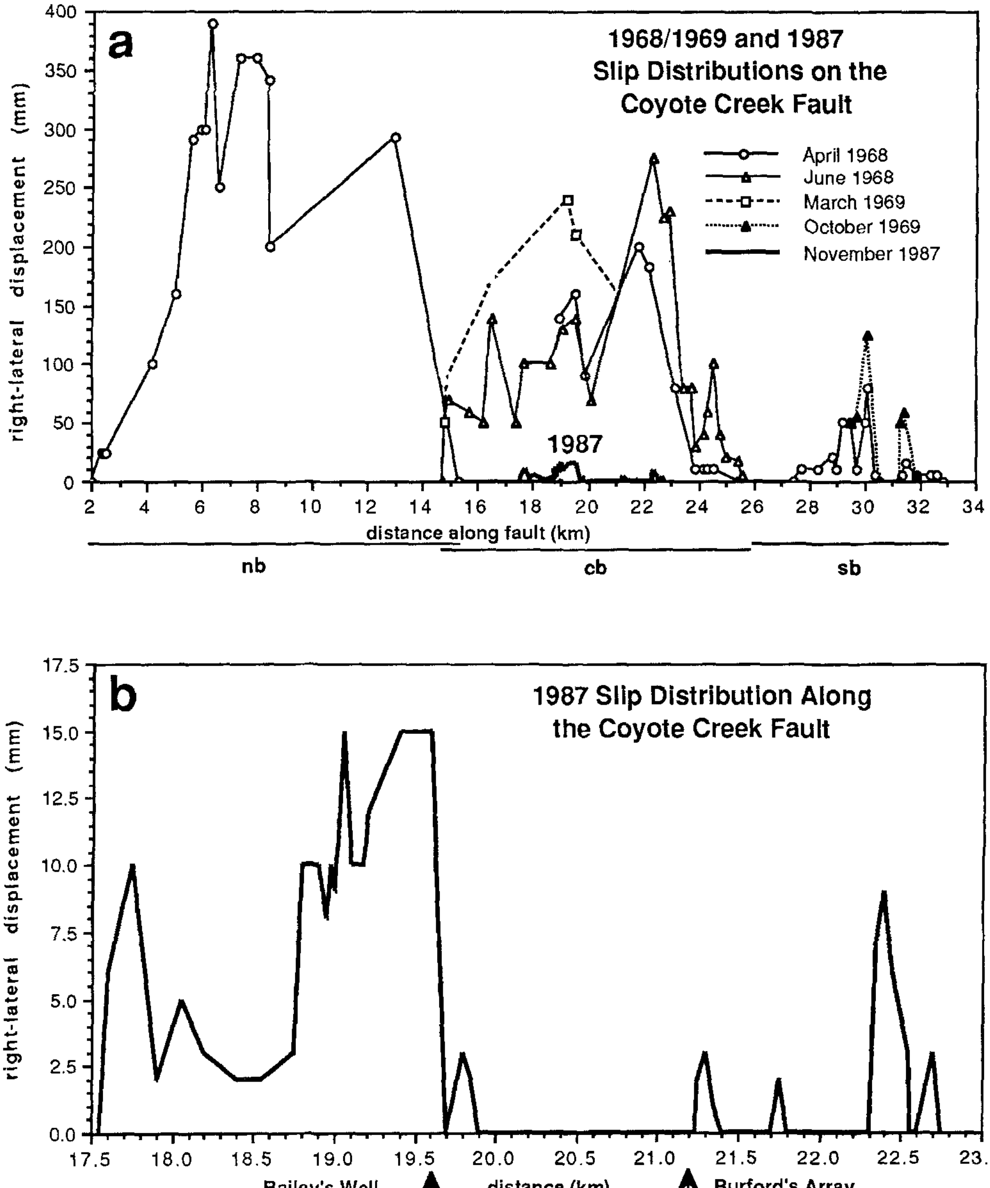


FIG. 3. Surface-slip distributions along the Coyote Creek fault in 1987; a) compared to slip measured in 1968 and 1969, taken from Clark (1972a), and b) enlarged to show details of the 1987 slip. The north break (nb), central break (cb), and south break (sb) of the 1968 rupture are indicated, corresponding to Figure 1. Locations of the alinement array at Bailey's Well and Burford's alinement array are also shown. Kilometer grid from Clark (1972a, Plate 1.1).

northeast trending fault. This fault has produced roughly 100 m of right-lateral separation of a surface mapped as Pleistocene or Holocene in age by Sharp and Clark (1972). This observation is a curiosity that warrants further investigation. It seems that the termination of slip in 1987 coincides with this fault intersection, suggesting to us that perhaps the fault intersection impeded propagation of the new surface rupture farther to the northwest.

Termination of slip at the southeast end of the new breaks, at about 22.8 km, is associated with a splay toward the southwest that occurred in the 1968 rupture.

This area is also identified by Sibson (1986) as adjacent to a right step in the fault trace of about 1 km. Because the fault step here is a broad feature, this apparent spatial relation may be coincidental.

In general, new surface slip did not occur where the 1968 surface rupture pattern was complex, for instance between about 20 to 21 km distance along the fault, near where the Old Kane Spring dirt road crosses the fault. In this area, a gap in 1987 slip occurred (Fig. 3), and we note that this area corresponds to a section of the 1968 rupture across which multiple fault strands broke.

Correlation of 1987 Slip Locations 1968 Rupture Characteristics

New slip in 1987 occurred along parts of the 1968 rupture central break that had large amounts of afterslip and significant vertical components of slip in association with that event. The segment of new ruptures along the Ocotillo Badlands (Fig. 1) had the largest and most persistent afterslip from 1968 through the early to mid-1970's, and it has Holocene scarps. Cracking was observed through 1976 along parts of the central break (M. M. Clark, unpublished data). Most of the 1987 rupture occurred along parts of the central break where 1968 rupture followed a single trace, without mappable en-echelon fractures (Clark, 1972a).

A secondary fault that splays from the central break of the Coyote Creek fault ruptured both in 1968 and 1987. This strand apparently did creep after the 1968 rupture, but only through March 1969, as observed by Clark (1972a, and unpublished data). Nearly on line with the northeastward projection of this secondary fault, and just south of highway 78, minor surface fractures with insignificant displacement were noticed after the November 1987 events (Hudnut *et al.*, 1989).

The north break of 1968, which had up to 380 mm right-lateral slip then, did not slip in 1987. In 1968, this segment had local vertical components of slip, but no reported afterslip; it also has Holocene scarps. Surface rupture in 1968 along this segment, even at its highest amounts of slip, occurred as partitioned displacement across multiple strands, typically en-echelon cracks. On 28 November 1987, between 1330 and 1645 hr (PST), a series of spot checks was made along the north break at the following locations (given in kilometers from the NW end of 1968 rupture from Plate 1 of Clark, 1972a): 3.5, 5.4, 6.7, 8.7, 10.1 to 10.5, and 12.0. No new slip was observed at any of these locations during that interval.

The south break of 1968 had afterslip from that event but did not slip in 1987. This segment also showed evidence of rupture within perhaps a few decades before the 1968 earthquake (Clark, 1972b). In 1968, this break had only local minor vertical components of slip, and had lesser right-lateral displacements than did the north and central breaks. En-echelon and multiple cracks also typified this fault segment in 1968. This segment is not marked by Holocene scarps. The south break was geographically closest of the 1968 segments to the Superstition Hills events. Spot checks were made at kilometer 30.6 to 33 between 1500 and 1650 hr on 24 November 1987, and at kilometer 27.8 and 30.6 to 31.6 on 3 December 1987. No new slip was observed at any of these locations during these inspections.

Discussion

Some correlations are possible between the local occurrence of characteristic features in the 1968 rupture with the location of triggered slip in 1987. Correspondence with large afterslip from 1968 through 1971 to 1976 suggest that the 1987 breaks are a continuation of afterslip. This will be discussed further below. The observed correlation of 1987 slip with single breaks along the main fault trace in 1968 and the presence of Holocene scarps may indicate parts of the fault with more accumulated or concentrated long-term slip. A possible explanation is that these segments have a smoother fault plane close to the surface, and are therefore easier to break and detect in a small creep event. The apparent correspondence with a large vertical slip component in 1968 has no explanation obvious to us.

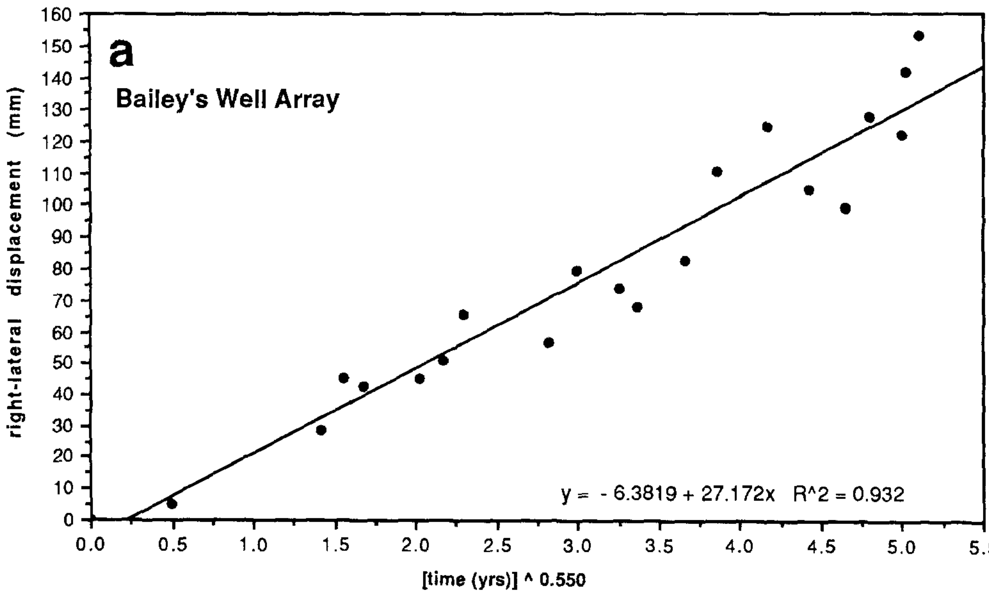
Afterslip on the Coyote Creek Fault Since 1968

Afterslip in 1968 occurred only on the central and south breaks of the Coyote Creek fault (Clark, 1972a; Burford, 1972; Louie *et al.* 1985), where sediments kilometers thick bury the basement (Hamilton, 1970). On the north break, where uplifted basement (forming Borrego Mountain) on the southwest of the fault contacts sediments northeast of the fault, there was insignificant afterslip. Thus, large amounts of afterslip from the 1968 rupture correlated spatially with the existence of thick sediments. This supports the hypothesis that afterslip represents stable sliding in the upper few kilometers of sediments, as suggested by Scholz *et al.* (1969) for the Parkfield 1966 event, and as documented by Mason and Crook (1988) for the 1979 Imperial Valley event. Marone and Scholz (1988) have proposed that velocity strengthening within unconsolidated sediments may explain this behavior.

Louie *et al.* (1985) postulated that the creep at the Bailey's Well array (location shown on Fig. 2) they observed from 1971 through 1985 was unlikely to be "residual seismic deformation due to the 1968 event," that is, afterslip. They based this argument on roughly a factor of 2 higher creep rate at Bailey's Well than the extrapolated rate at Burford's array to the southeast. Considerable variation in rates of afterslip along strike occurred after the Borrego Mountain event of 1968, and also after the Parkfield 1966, Imperial Valley 1979, and Superstition Hills 1987 events. Based on fresh cracks through March 1969, afterslip was reported at Bailey's Well but not at Burford's array. Also, new surface slip in 1987 was much greater at Bailey's Well than near Burford's array. It is therefore possible that the higher creep rate Louie *et al.* (1985) observed at Bailey's Well is indeed afterslip from the 1968 event, despite the discrepancy in creep rate they noted.

Data from Bailey's Well and Burford's array are compared in Fig. 4. Included are previously unpublished data from Caltech surveys from 1969 through 1971 at Bailey's Well (S. F. McGill, written comm., 1988), and from resurveys by Burford since 1972 (R. O. Burford, written comm., 1988). In the month including the November 1987 earthquakes, 21 ± 20 mm of dextral slip occurred at the Bailey's Well array (McGill *et al.*, 1989). At this location, 15 mm of new right-lateral slip was measured on 28 November 1987 (Figs. 2 and 5). When remeasured in late August of 1988, Burford's array had an additional 15.8 ± 1.2 mm of dextral slip since the previous measurement in late October of 1979. No new slip in 1987 was measured on surface cracks at this site, but 2 to 3 mm occurred only about 100 m southeast of that array (Fig. 2).

The alinement array data from the past two decades provide constraints on the behavior of the Coyote Creek fault since its rupture in 1968. We have attempted to fit the alinement array data with simple functions; linear, logarithmic, and power law. The best fitting functions of each type were obtained by least-squares regression. A linear function would fit the data best if the fault behavior is characterized by a constant rate of creep. Instead, afterslip has been found to be characterized by a creep rate that decreases with time. Typically afterslip data are well fit by semilogarithmic functions (Scholz *et al.*, 1969). Power-law functions have been found to best fit some of the afterslip data collected along the Superstition Hills fault by Williams and Magistrale (1989). Recent work on creep phenomena (e.g., Wesson,



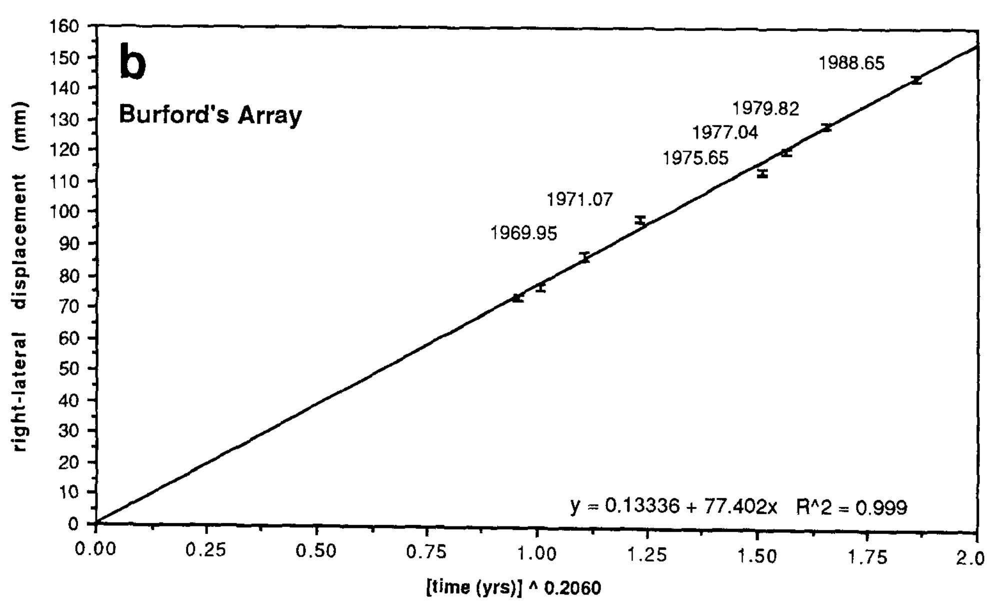


FIG. 4. Data from alinement arrays on the central break of the 1968 rupture. The data from a) the Caltech array at Bailey's Well (Louie *et al.*, 1985, S. F. McGill, written comm., 1988) and b) Burford's array (R. O. Burford, 1972; written comm., 1988) are independently fit best by power-law functions. Such functions are known to characterize afterslip. The origin on both graphs is at the time of the initial survey, at which time displacement is equal to zero. For Bailey's Well, the initial survey was on 15 March 1969. For Burford's array, the initial survey was on 25 April 1968. To produce the time axes on these graphs, time (in yr) since the initial survey was raised to the power b.

FIG. 5. New right-lateral slip of 15 mm on north side shoulder of dirt road at Caltech alinement array "Bailey's Well." The alinement array resurvey found 21 ± 20 mm right-lateral displacement at this location (McGill *et al.*, 1989). Photo taken on 28 November 1987 at about 1300 hr (PST).

1988) has suggested the use of physically based models to fit various creep observations, and it may be useful in the future to fit the alinement array data used here with these more sophisticated functions. Our attempt here, however, is to model the data approximately with these simple functions.

The method used here was to represent the first survey of each array by zero time and zero displacement. Thus the best fitting curve should presumably pass through the origin (though it is not forced to do so). Also, since we wish to fit the longest-period trends in the data, a function that fits the most recent data best is preferable (though this criterion is not mathematically forced either). The method for evaluating the best fit was to maximize the correlation coefficient, a measure of the goodness of fit.

We have used the pairs of benchmarks farthest from the fault trace in our analysis. For Bailey's Well, the endpoint benchmarks are a distance of about 800 m apart, whereas for Burford's array, the endpoint marks are about 200 m apart. It has been suggested that baseline length may influence the type of function that will provide the best fit to afterslip data (Bilham, 1989). We have chosen to use the longest available baselines at each of the two sites, primarily because benchmarks closer to the fault at Bailey's Well are unstable.

The Bailey's Well data (Fig. 4a) are fitted best by a power-law function of the form $S = aT^{b}$, in which S is total slip, T is time since the 1968 earthquake in yr, and a and b are constants that may be varied to fit the data. We determined these constants to be $b = 0.55 \pm 0.05$ and $a \approx 27$ mm. Because of scatter in the data, it is also possible to satisfactorily fit these data with either a linear or semi-logarithmic function. Compared to the best linear curve fit, the data are concave downwards, and compared to the best logarithmic curve fit, the data are concave upwards. The power-law function shown yields the best fit, based both on maximum correlation coefficient and on visual inspection.

Data from Burford's array (Fig. 4b) are also best fit by a power-law function. A linear function clearly does not fit these data well. Either a logarithmic or power-law function does fit the data well. The highest correlation coefficient is obtained for a power-law function in which $b = 0.2060 \pm 0.005$ and $a = 77.40$ mm. The power-law function intersects the origin, to well within the standard deviation of a single survey, but the best fitting logarithmic function misses the origin by almost 50 mm. The power-law function fits the 1988 observation to within 0.25 mm, whereas the logarithmic function fits that point only to within about 4 mm. Thus there are two other criteria (besides the highest correlation coefficient) to prefer the power-law function over the logarithmic function as the best fit to the observations from Burford's array.

The discrepancy between values of b at the two sites, 0.55 at Bailey's Well and 0.206 at Burford's array, is large. Less variation with position along strike than this has been observed for the Superstition Hills fault (Williams and Magistrale, 1989). It is not apparent to us why the discrepancy is so great between these arrays that are only 2.5 km apart.

It is also noteworthy that there are significant yet small discrepancies between the observations and the best-fitting power law function at Burford's array (Fig. 4b). These discrepancies may point to a different explanation of the observations than simple afterslip, and future monitoring of slip here will help to evaluate that possibility. From continuous observation of the Superstition Hills fault afterslip (Bilham, 1989), it is evident that discrete creep events of from several mm to about 15 mm amplitude occur, and that the cumulative sum of these events through time produces the characteristic afterslip curve. McGill *et al.* (1989) show another consideration, that, during afterslip, strain relaxation occurs out to at least 250 m distance from the fault. The release of afterslip is commonly observed to be episodic, and the discrepancies at Burford's array may thereby be explained and also consistent with the afterslip interpretation.

In summary, all of these alinement array data, in particular Burford's data, are best fit by power-law functions, and adequately fit by logarithmic functions. These data are thus most simply explained as afterslip from the 1968 event. We suggest further that the 1987 triggered slip event along the Coyote Creek fault represents a distinct episode of this continuing afterslip.

Triggered Slip: A Valid Earthquake Precursor?

A simple test for validity of triggered slip as an earthquake precursor is to consider its documented occurrences that were referred to in the introduction. Table 1 shows that, despite apparent precursory relationships on the Imperial fault and Superstition Hills fault, triggered slip also occurs after large earthquakes, as on the Imperial fault and Coyote Creek fault. Slip events in 1987 on the Coyote Creek fault and in 1981 and 1987 on the Imperial fault differ in a notable way from the other triggered slip events. They follow major ruptures of these faults and occur early enough in the earthquake cycle so they cannot reasonably be considered precursors to the next major event.

TABLE 1

OCCURRENCES OF TRIGGERED SLIP

Event	SAF	SHF	IF	CCF
1968	yes	yes	yes	eq
1979	yes	yes	eq	maybe*
1981	no†	yes	yes	no†
1986	yes	no (?)	no (?)	no (?)
1987	yes‡	eq	yes	yes

"Eq" indicates an earthquake. "No" is queried where absence of observations is a possible reason. SAF refers to the southern segment of the San Andreas fault: other abbreviations are; SHF, Superstition Hills fault; IF, Imperial fault; CCF, Coyote Creek fault.

* Louie *et al.* (1985) found a high creep rate over the period November 1979 through 1982. Fuis (1982) mentioned unpublished alinement array data that suggested slip but we find these data were noisy (Fig. 4). No surface fractures were observed.

† Reported by Sharp *et al.* (1986a).

‡ McGill *et al.* (1989) documented triggered slip with creepmeter data. No surface fractures with significant displacement were observed, however.

The coincidence of triggered slip in 1968 on the Imperial fault with an ensuing $M > 6$ event in 1979 led Sieh (1982) to suggest that triggered slip may be an earthquake precursor. Table 1 shows that additional empirical evidence, accumulated after the 1981, 1986, and 1987 events, does not follow Sieh's hypothesis. Triggered slip has clearly both followed and preceded $M > 6$ events. We therefore suggest a corollary to his hypothesis: if this phenomenon is to be identified as a precursor based on empirical evidence, it should also be shown that triggered slip events are occurring late in the earthquake cycle, perhaps as a surface expression of precursory slip at depth, rather than merely as afterslip of the previous event.

Creep at an unexpectedly high rate (in comparison to predictions from afterslip curves) late in an earthquake cycle could indicate precursory slip at depth. The mechanism for such behavior could be tertiary creep (Scholz, 1972; Kranz and Scholz, 1977). In the laboratory, this behavior is accompanied by acoustic emissions, presumably analogous to microearthquakes. Precursory creep acceleration late in an earthquake cycle may therefore be accompanied by anomalously high seismicity.

Afterslip and Triggered Slip on other Faults in the Region

Afterslip of the 1979 earthquake on the Imperial fault had decayed to a rate of about 13 mm/yr when the recent episode of creep occurred, possibly triggered by the November 1987 Superstition Hills earthquakes (Mason and Crook, 1988; McGill *et al.*, 1989). This slip event produced surface cracks with significant displacements (Sharp, 1989), and conventionally would be considered a triggered slip event. Moreover, the 1979 afterslip appears confined to the upper 4 km of the fault plane, indicating that afterslip involves mainly the sediment cover (Mason and Crook, 1988). Thus, the 1987 triggered slip event probably represents a continuation of afterslip from the 1979 event.

Afterslip of the 1940 earthquake, according to Harsh (1982), followed approximately the 1979 afterslip curves where highway S-80 crosses the fault. If correct, by the late 1960's the afterslip rate should have diminished to about 1mm/yr at this site. Cohn *et al.* (1982) showed that from 1967 through mid-1979 the creep rate there was actually nearly 6 mm/yr, including the 1968 triggered slip event. This discrepancy (noted by Harsh, 1982) indicates that an intermediate- to long-term rate increase may have been precursory to the 1979 rupture. High seismicity on the fault also occurred sporadically during these 12 yr of high creep rate (Johnson and Hill, 1982; Johnson and Hutton, 1982), but may not have been anomalous. Interestingly, a creep episode was observed by leveling between October 1977 and January 1979 (Sharp and Lienkaemper, 1982) and by alinement array remeasurements between June and November 1978 (Cohn *et al.*, 1982). The suggestion that this creep was a precursor to the 1979 event is weakened by the observation that other creep events had occurred in the previous decade as well, and that these creep episodes were not necessarily anomalous.

For the Superstition Hills fault, Hudnut and Sieh (1989) have proposed that the penultimate slip event may have been associated with the poorly located April 1906 or June 1915 earthquakes in the Imperial Valley. If it is assumed that afterslip of the 1987 event is similar to the afterslip of the penultimate event, the logarithmic curve fit to their afterslip data for the 1987 event can be used to extrapolate rates following the previous event. Using this approach, and taking 1906 to 1915 as the starting point, the afterslip rate should have declined to 1.0 mm/yr by the late 1960's. They conclude, however, that the previous event could have been as early as 1663 $\pm$ 22 A.D. In that case, the rate should have declined to $<$0.2 mm/yr by 1987. The alinement array data for this fault indicate an average creep rate of 0.9 mm/yr since 1967 while creepmeter data at a different site showed a steady rate of 0.5 mm/yr from 1969 to 1979 (Louie *et al.*, 1985). Thus, it appears that afterslip following the previous earthquake on the Superstition Hills fault could explain the triggered slip events since 1967. There is no indication of intermediate- to long-term accelerated creep preceding the 1987 rupture, but it cannot be ruled out because of the wide range of possible dates for the previous event. There apparently was no anomalously high seismicity on this fault during the few decades preceding the 1987 rupture.

For the San Andreas fault, Sieh and Williams (1989) have shown that the southern segment probably has not ruptured in a large seismic event in the past three centuries. From sites at Indio, Ferrum, and Salt Creek, they obtained a record of slip following the latest large earthquake, dated at 1663 ± 22 A.D. They conclude that their data are interpreted most simply as indicating a steady creep rate of 3 to 4 mm/yr since the last event. Their data show that the creep rate in the past 80 yr has probably been lower than the rate averaged over the past three centuries. They further conclude that a nearly constant creep rate for the past 80 yr means that triggered slip events there since 1968 should not be considered as short-term precursors to the next event.

The data of Sieh and Williams (1989), however, are also consistent with a decrease in creep rate that would be expected if afterslip is the mechanism of creep there. Perhaps triggered slip events recorded in the past 20 yr on this fault are still afterslip from the last event. A logarithmic function has been fit to their data, and yields a predicted creep rate in the past two decades that is lower by a factor of 2 to 3 than the observed rate in that interval. Their slip for the past 80 yr appears to also be higher than expected from this afterslip hypothesis. The southern San Andreas fault has been seismically quiet for at least the past few decades.

Fault Segment Characterization and Delimitation

Along-strike extent of triggered slip has been used in recent earthquake hazard studies as a criterion to characterize and/or implicitly delimit fault segments. Examples are the Superstition Hills fault and the southern San Andreas fault (Wesnousky, 1982; Working Group on California Earthquake Probabilities, 1988). Surface slip in the 1987 Superstition Hills fault rupture extended beyond its previously delimited southeast end (Sharp *et al.*, 1989). If triggered slip represents afterslip, and considering that afterslip and triggered slip have only been observed where thick sediments cover faults, it follows that the along-strike event of triggered slip may indicate nothing more about a fault segment than that thick sediments locally cover the fault, and that it ruptured previously. For instance, the Indio Hills would mark the northwest end of the Coachella Valley segment of the San Andreas fault, if only the extent of mapped triggered slip were used to delimit that segment (Williams *et al.*, 1988). Only 10 km northwest of the Indio Hills, however, both branches of the San Andreas fault are bounded on the northeast by uplifted basement—similar to the contact along the north break of the 1968 rupture on the Coyote Creek fault where no afterslip or triggered slip has been observed.

In special cases where the entire fault is covered by thick sediments, as on the Imperial fault, the extent of triggered slip along a fault may be more useful for delimiting fault segments. Characterizing or delimiting fault segments solely on the basis of where triggered slip has occurred may be inaccurate, however, particularly where depth to basement or soil characteristics vary substantially along strike of the fault.

CONCLUSIONS

We have documented new slip on the Coyote Creek fault, mapped shortly following the 24 November 1987 Superstition Hills earthquakes, and presumably triggered by them. Surface cracking along segments of the fault continued through 1976 on the central break and through 1971 on the south break. This deformation is considered afterslip from the 1968 event. Based on alinement array data, we argue that the 1987 slip event is also afterslip. Triggered slip has been suggested as an intermediate-term precursor to $M > 6$ earthquakes. Considering all documented occurrences of this fault behavior to date, it seems to occur commonly both following

$M > 6$ events, as in the 1987 example on the Coyote Creek fault, and preceding them as on the Superstition Hills fault. On the Imperial fault, triggered slip has both preceded and followed the 1979 earthquake. Thus, we question the value of the phenomenon as an empirical earthquake precursor unless the slip history of the fault is well known.

Further, since afterslip typically follows logarithmic or power-law decay (Wesson, 1988) after an earthquake, it may continue at low rates late in an earthquake cycle as discrete aseismic creep events that are commonly triggered by earthquakes on nearby faults. Triggered slip may in general represent afterslip, and thus not necessarily have anything to do with precursory fault activity.

If an observed creep rate is higher than expected from afterslip curves from the previous event, a precursory creep rate increase may be suspected. The pre-1979 creep rate on the Imperial fault was higher than expected from sparsely documented afterslip of the 1940 event. This possibly accelerated creep was accompanied by microseismicity. The creep rate for the San Andreas fault in the past 80 yr, may also be higher than expected (if one assumes afterslip instead of steady creep), but the lack of microseismicity seems to exclude precursory tertiary creep as the mechanism. Finally, the large range of possible dates for the penultimate event on the Superstition Hills fault precludes determining whether the creep rate from 1967 through October 1987 was anomalous or not; this fault did not show anomalous seisimicity during that period.

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