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Cross-Fault Triggering in the November 1987 Superstition Hills Earthquake Sequence, Southern California

K. W. Hudnut[1], L. Seeber, and J. Pacheco[1]

Lamont-Doherty Geological Observatory, Palisades, New York

Abstract. Two large strike-slip ruptures 11.4 hours apart occurred on intersecting, nearly orthogonal, vertical faults during the November 1987 Superstition Hills earthquake sequence in southern California. This sequence is the latest in a northwestward progression of earthquakes (1979, 1981, and 1987) rupturing a set of parallel left-lateral cross-faults that trend northeast between the Brawley seismic zone and Superstition Hills fault, a northwest trending main strand of the San Jacinto fault zone. The first large event (M_S=6.2) in the 1987 sequence ruptured the Elmore Ranch fault, a cross-fault that strikes northeasterly between the Brawley seismic zone and the Superstition Hills main fault. The second event (M_S=6.6) initiated its rupture at the intersection of the cross-fault and main fault and propagated towards the southeast along the main fault. The following hypotheses are advanced; (1) slip on the cross-fault locally decreased normal stress on the main fault, and triggered the main fault rupture after a delay; and (2) the delay was caused by fluid diffusion. It is inferred that the observed northwestward progression of ruptures on cross-faults may continue. The next cross-fault expected to rupture intersects both the San Andreas fault and the San Jacinto fault zone. We hypothesize that rupture of this cross-fault may trigger rupture on either of these main faults by a mechanism similar to that which occurred in the Superstition Hills earthquake sequence.

Introduction

The transition zone between the Gulf of California ridge-transform system and the southern termini of continental transform faults of southern California comprises a set of parallel faults with left-lateral motion that trend northeast (Fig. 1). These faults, here termed "cross-faults" are approximately evenly spaced and nearly orthogonal to the main right-lateral faults they abut. Bounding faults are the San Andreas fault and Brawley seismic zone to the east and the San Jacinto fault zone to the west.

The Superstition Hills earthquake sequence of November 1987 (Fig's 1 & 2) demonstrated that cross-fault rupture can trigger rupture of a main fault. The purpose of this paper is to explore the mechanical relationship between the cross-fault "foreshock" and the main fault "mainshock" in the 1987 Superstition Hills earthquake sequence. Further, we discuss the apparent space-time progression of cross-fault ruptures across the region. We then infer that future large earthquakes on specific cross-faults could be foreshocks to a major earthquake on the San Andreas fault, or perhaps the San Jacinto fault zone.

The 1987 Superstition Hills Sequence

Seismicity Data. A cluster of seismicity developed in April 1987, near the intersection of the Brawley seismic zone and the eventual rupture zone of the Elmore Ranch cross-fault

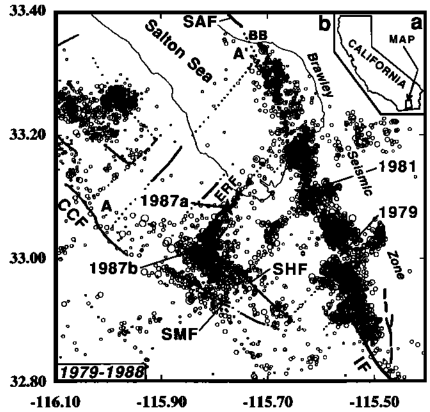

Figure 1. a) Inset map showing location in California. b) Seismicity and known and inferred faults between the San Jacinto fault zone and Brawley seismic zone (BSZ). Note that epicenters in all figures are from the southern California network catalog (Caltech; C.I.T. and U.S. Geological Survey; U.S.G.S.). Nucleation points of the 1979, 1981, and 1987 cross-fault ruptures, and the 1987 Superstition Hills main fault rupture (M=6.6) are indicated by stars. The other faults shown are: San Andreas fault (SAF), Imperial fault (IF), Coyote Creek fault (CCF), Superstition Mountain fault (SMF), Superstition Hills fault (SHF), and Elmore Ranch fault (ERF). Also shown is a geologically mapped zone of cross-faults from A to A' that we name the "Extra" fault zone. Bombay Beach is identified by **BB**.

(ERF). The first large event, M_S=6.2, occurred at 5:53 pm (PST) on Nov. 23, 1987, shortly after several small co-located foreshocks. The event was located on the ERF, about ten kilometers northeast of the Superstition Hills fault. Early epicenters defined a northeast trend (Fig. 2a) indicating a rupture over the entire length (about 20 km) of that cross-fault [*Magistrale et al.*, in press].

The largest event of the sequence, M_S=6.6, occurred at 5:16 a.m. (PST) on Nov. 24, 11 hours and 23 minutes after the M>6 foreshock. This mainshock nucleated near the intersection of the cross-fault with the Superstition Hills "main" fault (SHF). Aftershocks of this event defined a broad zone trending southeast, along the SHF (Fig. 2b), but concentrated near the northwest end of the SHF, where the cross-fault and main fault intersect.

Surface Ruptures. Surface slip was well-developed on both the cross fault and the main fault, generally increasing with distance away from their intersection [*Kahle et al.*, 1988; *Budding and Sharp*, 1988; *Williams and Magistrale*, in press; *Hudnut et al.*, in press]. The pattern of surface rupture was complex in this area, with much normal faulting in the eastern quadrant of the intersection between the main and cross faults. Thorough mapping efforts revealed no rupture on the SHF northwest of the intersection.

As much as 13 cm of left-lateral surface slip was measured on individual strands of northeast-trending faults on and after Nov. 24 [*Hudnut et al.*, in press]. The Nov. 24 mainshock produced surface offset approaching 80 centimeters along the central part of the SHF as of May 1988, with offset tapering to zero at both ends of the main fault rupture [*Williams and*

[1]also at Department of Geological Sciences, Columbia University, New York

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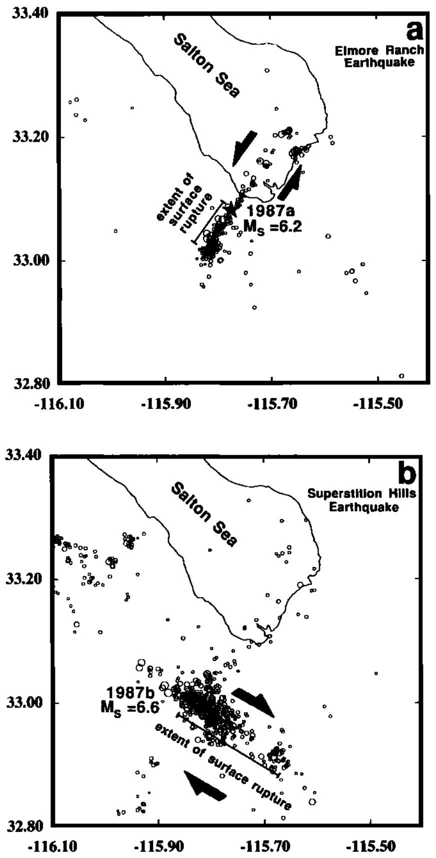

Figure 2. **a**) Seismicity including foreshocks and aftershocks of the Nov. 23 Elmore Ranch fault event, until the time of the main event on the Superstition Hills fault. **b**) Main event of the Superstition Hills sequence, and seismicity following it through March 1988. Interestingly, aftershock activity along the Elmore Ranch fault decreased following the main fault rupture. The arrows showing sense of slip on these fault planes are determined from surface ruptures on both the cross-faults and the Superstition Hills fault. Fault plane solutions (not shown) are consistent with the sense of displacement indicated by these arrows.

Magistrale, in press]. Significant afterslip on the SHF was observed shortly after the main earthquake, and is continuing a year later at much reduced rates. In contrast, all slip on the cross-faults appears to have occurred during the earthquake sequence, with no afterslip yet observed on the cross-faults since the evening of Nov. 24.

Cross-Fault Triggering in the 1987 Sequence

The temporal and spatial relationship of the two largest events in the Superstition Hills earthquake sequence implies a direct causal relationship between rupture of a cross-fault (Fig. 2a) and subsequent larger rupture on an intersecting main fault (Fig. 2b). Specifically, the coincidence between terminations of the surface breaks and the intersection of the cross-fault and main fault, and also nucleation of the main shock near that intersection, suggest that the cross-fault controlled behavior of rupture of the main fault. We interpret the relationship as follows: slip on the cross-fault (the ERF) apparently changed normal stress (σ_n) on the main fault (the SHF), increasing σ_n to the northwest, and decreasing σ_n to the southeast, of the faults' intersection. The change in Coulomb stress (σ_C) resulting from this decrease in σ_n southeast of the intersection would initially be counteracted by a decrease in pore pressure (P_p). The σ_C would therefore increase instantly by some amount, and then gradually continue to increase until P_p returned to its initial value.

To test our hypothesis, we model the perturbation of stresses on the main fault (SHF) caused by a displacement on the cross-fault (ERF). Our model is based on a 2-D crack in a linear, poro-elastic, saturated material that undergoes a sudden stress-drop [*Rice and Cleary*, 1976]. This simple model configuration is shown in Fig. 3a. Slip on the ERF is represented by an elliptical slip distribution. Equation 47 from *Rice and Cleary* [1976], and equation 2 (and appendix) from *Li et al.* [1987] were used to calculate changes in stress and pore pressure that would result from the modeled slip event.

Fig. 3b shows the calculated instantaneous changes in σ_n, P_p, and shear stress (τ_s), along the main fault (SHF) caused by the unit stress drop on the cross-fault (ERF). The change in σ_n on the main fault is greater than the τ_s drop on the cross-fault. On the side of the fault intersection where σ_n decreases, P_p also decreases, but the net effect is an increase in σ_C. The increase in σ_C brings the fault closer to failure (using $\sigma_C=\tau_s+\mu(P_p - \sigma_n)$, and $\mu = 0.75$). The modeling results show a 25 to 35% increase in σ_C on the main fault as the elastic response to slip on the cross-fault (Fig. 3c); that elastic effect evidently was insufficient to trigger main fault rupture. With time, weakening of the main fault equals about 45 to 50% of the τ_s drop on the cross-fault (Fig. 3d). The Superstition Hills sequence can thus be modelled as weakening of the main fault caused by preceding slip on a cross-fault, which in turn brings the main fault to failure.

The observed 11.4 hour delay between foreshock and mainshock can be explained by fluid diffusion. For this effect, the relaxation time (t_r) is $t_r=L^2/4c$, where L is semi-rupture length and c is diffusivity [*Li et al.*, 1987]. Delay length, however, will also depend upon other material properties, and the amount of increase in σ_C needed to trigger rupture on the main fault. Because there is an immediate weakening of the main fault, followed by increased weakening within days to months, cross-fault triggering can occur immediately (as may have occurred in the Tango, Japan earthquake of 1927; C. Scholz, pers. comm.), or after a delay as in the Superstition Hills example.

Other effects such as stress corrosion may also affect time-dependence. Stress corrosion on the fault [*Das and Scholz*, 1981] might be enhanced as P_p is restored on the main fault, causing fluids to migrate into the fault. A resulting gradual decrease in the coefficient of friction on the fault surface (μ) could allow failure of the main fault at a lesser shear stress. Other effects may possibly explain the delay, such as creep on viscous portions of the cross-fault [e.g., *Given and Stuart*, 1988]. A fluid diffusion model for the delay is clearly not the only solution, but we feel that fluid diffusion is likely to be an important mechanism in cases involving orthogonal faults.

Discussion and Conclusions

Future Shocks? A progression of cross-fault ruptures from southeast toward northwest traversed the Brawley seismic zone (Fig. 4), with events in 1979 [*Johnson and Hutton*, 1982], 1981 [*Nicholson et al.*, 1986], and 1987. The 1979 event (M_S=5.7) was an aftershock of the 1979 Imperial Valley earthquake; the 1981 event (M_S=6.0) was the main shock of a relatively minor sequence; and the 1987 event was the foreshock of the Superstition Hills sequence (M_S=6.2). Progression of these events indicates a pattern in space and time that may continue with rupture of the next zone of cross-faults towards the northwest (labelled A-A' in Fig. 1). For the purposes of this paper, we name this the "Extra" fault zone after a nearby surveying benchmark bearing that name. Progressions like this one have long enticed earthquake researchers [e.g., *Mogi*, 1968], but their mechanisms are not well understood. In the Imperial Valley, individual earthquake swarms can migrate from north to south [e.g., *Johnson*, 1979], but the relation of this to the migration of larger events over the greater distances and times observed here is not clear.

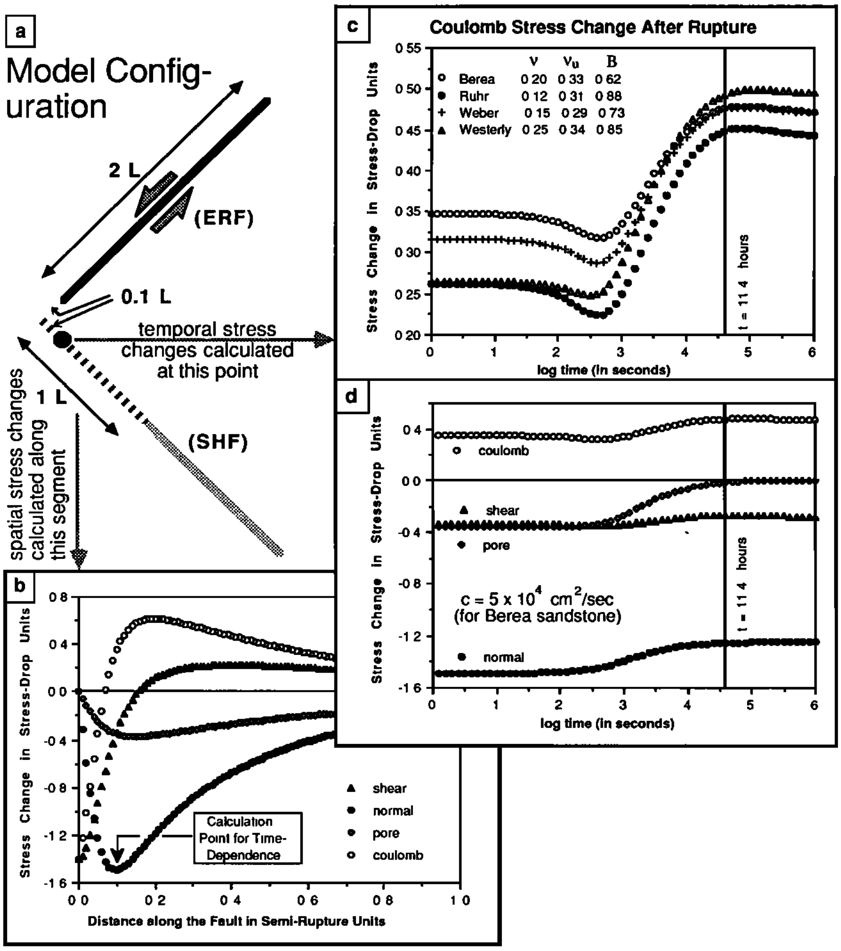

Figure 3. **a**) The model is set up with a single stress-drop unit along a cross-fault with semi-rupture length of L. **b**) Stress changes one second after cross-fault rupture are calculated along an axis (shown as a dashed line) displaced 0.1 L from the crack tip. **c**) Change in σ_C with time (as calculated on the main fault at 0.1 L away from the intersection) depends upon material properties of rock near the fault. Here the use of laboratory values for four rock types demonstrates the variations in σ_C that result from varying drained (ν) and undrained (ν_u) Poisson's ratio, and Skempton's parameter (B). **d**) Changes in stresses with time after the cross-fault slip event, calculated with laboratory values for Berea sandstone. In parts **c** and **d** of this figure, calculations used a value for diffusivity (c) of $5 * 10^4$ cm^2/sec.

Rupture of the Extra fault zone would weaken the southern San Andreas fault, possibly enough to cause nucleation of a rupture there. The cross-fault triggering of a major San Andreas fault rupture would depend mainly on the amount and distribution of slip that occurs in the cross-fault event, and the magnitude of shear stress accumulated across the southernmost San Andreas fault. It has been recognized that the southern San Andreas fault is probably in a late stage of the seismic cycle. Results from excavations at the Indio and Salt Creek sites [*Sieh and Williams*, in press] indicate that the last major event on the southernmost San Andreas fault was more than 300 years ago, about the time interval of earthquake recurrence there. In addition, geodetic observations [*Savage et al.*, 1986] show shear strain accumulation at about a factor of ten higher rate than the surficial creep rate during the past two decades [e.g., *Louie et al.*, 1985]. Alternatively, rupture of the Extra fault zone could trigger a large rupture on the San Jacinto fault zone, for instance on the Superstition Mountain fault (Fig. 1) that has not ruptured in historic time.

Other scenarios for initiation of the next great southern California event on the San Andreas fault have been considered. For example, a southern San Andreas fault rupture might nucleate near San Gorgonio Pass [*Sykes and Seeber*, 1985], or along fault jogs between the Indio Hills or Mecca Hills segments that *Bilham and Williams* [1985] describe.

The 1987 Superstition Hills earthquake sequence involved cross-fault triggering of a rupture on a main strand of the San Jacinto fault. A future rupture of the southern San Andreas fault may follow a similar mechanism on a larger scale. This scenario involves a large precursory event on a cross-fault, perhaps followed by a delay that might permit short-term prediction of a great southern California event, rupturing at least a 100 km long segment of the San Andreas fault. Alternatively, a large event on the southern San Andreas fault could similarly trigger a secondary event of magnitude about $6^1/_2$ on the Extra fault zone.

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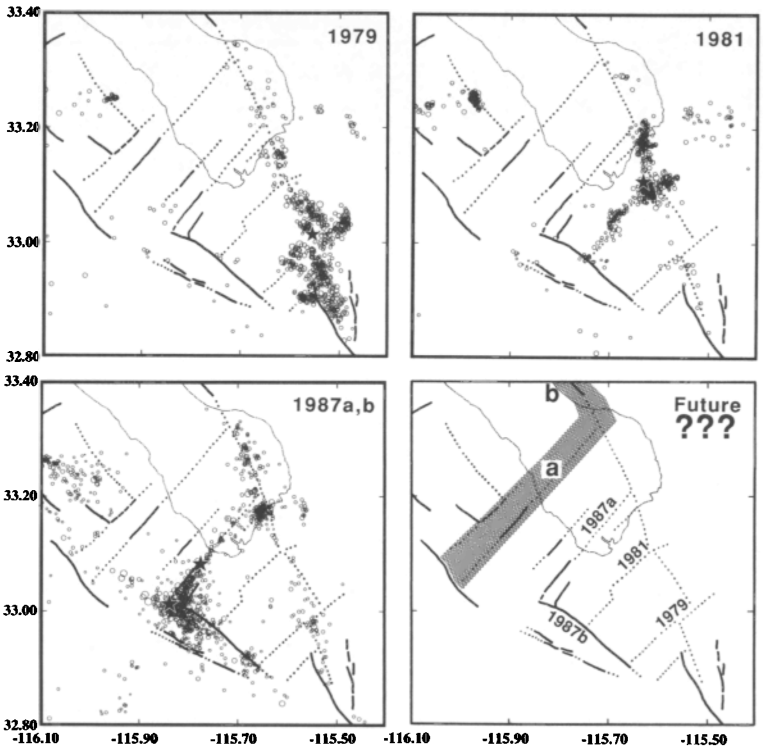

Figure 4. Northwestward progression of cross-fault ruptures and seismicity between the San Jacinto fault zone and the Brawley seismic zone from 1979 to 1988. The sequence began in 1979 with a M_S=5.7 aftershock (star) of the Imperial Valley earthquake. In 1981, the M_S=6.0 Westmorland earthquake (star) ruptured at least part of the next cross-fault to the northwest. In 1987, the Elmore Ranch fault ruptured (star) and triggered the Superstition Hills fault (star). In the future, it is possible that cross-faults still farther to the northwest in the Extra fault zone may trigger ruptures on either the southern San Andreas fault, or perhaps the Superstition Mountain fault. An earthquake nucleating on the San Andreas fault near Bombay Beach (**BB** in Fig. 1) could rupture at least the southern 100 km segment of this fault.

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K. W. Hudnut, J. Pacheco, and L. Seeber, Lamont-Doherty Geological Observatory, Palisades, NY 10964.

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