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THE ELMORE RANCH AND SUPERSTITION HILLS EARTHQUAKES OF 24 NOVEMBER 1987: INTRODUCTION TO THE SPECIAL ISSUE

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On 24 November 1987, two significant earthquakes occurred along the southern San Jacinto fault zone and related structural elements in southern California, not far from the International Border. These two events, the Elmore Ranch earthquake (M = 6.2 at 0154 GMT) and the Superstition Hills earthquake (M = 6.6 at 1315 GMT, both moment magnitudes from Sipkin, 1989), and their aftershocks have yielded a rich harvest of geological, seismological, and engineering data pertinent to the cause and effect of earthquakes in this region, where the southern San Jacinto fault zone enters the Salton Depression from the Peninsula Ranges bordering it on the southwest (Fig. 1). This special issue of the *Bulletin* presents 18 geologic and seismologic investigations of these earthquakes, a collection of papers born in El Centro, California, on 8 and 9 February 1988 at a meeting attended by approximately 60 scientists interested in these earthquakes for one reason or another.

As recounted by Magistrale *et al.* (1989), the sequence began with six colocated foreshocks to the Elmore Ranch earthquake. For 12 hrs following the first main shock, aftershocks occurred along a sharply defined northeast trend, extending from the northwest end of the Superstition Hills fault, under the southeastern margin of the Salton Sea, to the Brawley seismic zone. As evidenced by the northeast trend of this alignment, focal mechanisms for the Elmore Ranch earthquake and its aftershocks, and the zone of surface faulting that overlies these events, this episode of earthquakes principally involves left-lateral strain release on a fault structure that forms a conjugate pair with the Superstition Hills fault. The second main shock, the Superstition Hills earthquake, had an epicenter at the northwest end of the Superstition Hills fault, at the southwestern end of the seismicity alignment activated by the Elmore Ranch earthquake. Immediately afterwards, aftershocks initiated beneath the northwest-trending, right-lateral Superstition Hills fault, which ruptured along its entire mapped length—and, in fact, a bit more that had not been previously mapped (Sharp *et al.*, 1989).

Because the first main shock occurred just after sunset on 23 November and the second main shock occurred just before sunrise on 24 November (both local times), the relationship of the surface faulting events to the two earthquakes can only be inferred. Kahle *et al.* (1988) report that the Imler Road crossing of the Superstition Hills fault, near its southeastern end, was unfaulted in the early morning hours between the two main shocks but was observed to be faulted shortly after the occurrence of the Superstition Hills earthquake. By sunset of 24 November it had been established that the Superstition Hills fault had ruptured completely (Sharp *et al.*, 1989) and that a complex set of multiple, northeast-trending, left-lateral strands had also broken (Hudnut *et al.*, 1989b; Sharp *et al.*, 1989). The likely relationship, of course, is that the Elmore Ranch earthquake activated the northeast-trending faults, while the Superstition Hills earthquake broke the Superstition Hills fault. Sharp and Saxton (1989), however, suggest that at least 5 cm of right-

FIG. 1. High altitude photograph of southern California and northern Mexico, looking southwest (Frame 142-059R, U.S. Air Force, 17 July 1968). The southernmost part of the Salton Sea is the dark area in the lower right, and the western Imperial Valley appears as the checkerboard pattern on the left. Superstition Mountain stands above the otherwise nearly featureless fans near the center of the photograph. Principal strands of surface faulting for the 1987 earthquakes are shown in bold lines. The Superstition Hills fault, approximately horizontal, ruptured in its entirety. Also shown, in approximate form, are the northeast-trending, left-lateral, conjugate faults. The Elmore Ranch earthquake epicenter is indicated by the small solid circle between two of the northeast-trending faults. The Superstition Hills earthquake epicenter is shown by the symbol at the northwest end of the Superstition Hills fault. A portion of the Lake Coahuila shoreline, abandoned approximately 330 yrs ago, of interest to studies included in this Special Issue is shown as the thin line.

lateral slip existed on the northwestern end of the Superstition Hills fault at the time of the second main shock, from an analysis of small-aperture quadrilateral data extrapolated back to the origin time of the Superstition Hills earthquake.

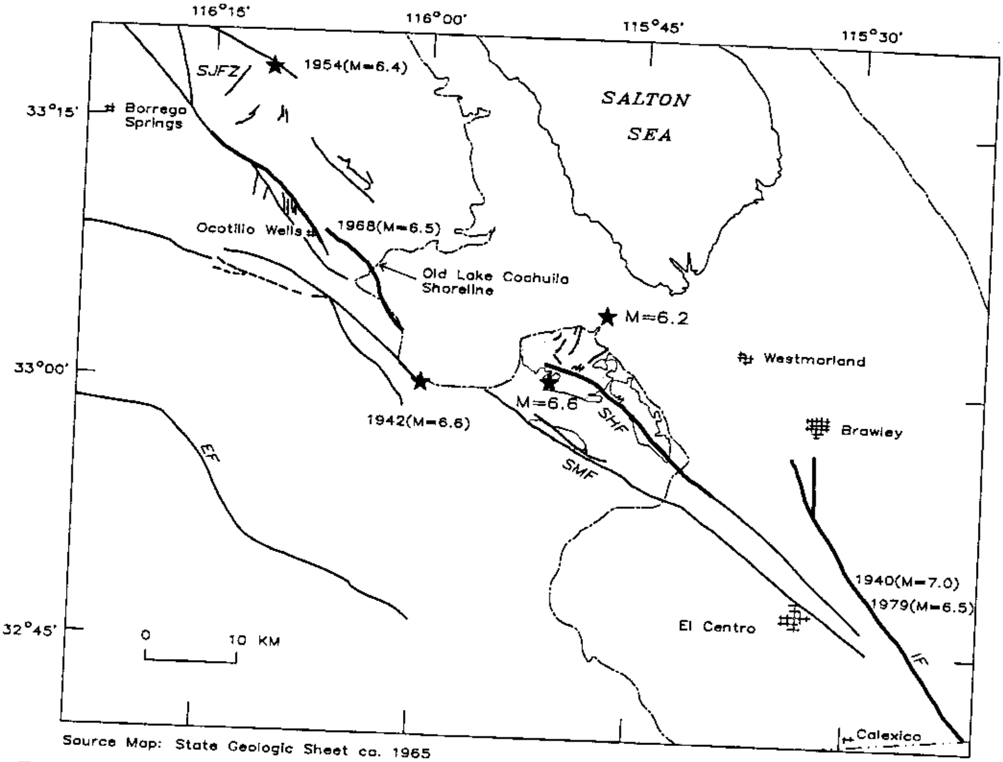
The Elmore Ranch and Superstition Hills earthquakes, then, are distinctly different earthquakes, each with its own manifestations, but at the same time they obviously share common mechanical relationships to one another. The most noteworthy of these involves the conjugate faulting expressed by these earthquakes and their aftershock distributions, the tectonic nexus being along the northwestern 4 km of the Superstition Hills fault where it takes a distinctly more westerly trend from its strands to the southeast. The geometry of the main shock epicenters, aftershock loci, and faulting relationships is such that the Elmore Ranch earthquake should decrease normal stress across most of the Superstition Hills fault, suggesting a triggering mechanism for the second main shock, its aftershocks, and rupture of the Superstition Hills fault (Hudnut *et al.*, 1989b). The nearly simultaneous activation of this conjugate fault pair, both with aftershocks and with surface faulting, is unique in the United States. In the global experience, such situations are known but rare; the 1927 Tango, Japan, earthquake, a much larger shock at $M = 8.0$, is perhaps the best known example (Richter, 1958).

Even so, abundant if less spectacular evidence for conjugate faulting and tectonics in the Salton Depression had been pointed out well before the 1987 earthquakes. Northeast-trending cross faults in the Superstition Hills appear on the Salton Sea sheet of the Geologic Map of California that is now more than 20 yrs old. Off-fault pods of seismicity following the 1968 Borrego Mountain earthquake define a line nearly orthogonal to the 1968 surface ruptures (Hamilton, 1972). Northeast-trending structures intersecting the Brawley seismic zone had been identified with seismicity data by Johnson and Hadley (1976), Johnson and Hill (1982), and Johnson and Hutton (1982). Through most of the 1980's, R. V. Sharp has been mapping northeast-trending faults in Quaternary sediments of the western Imperial Valley, while exploring this terrain for evidence of northwest-trending right-lateral members of the southern San Jacinto fault zone east of the known segments (Fig. 2).

While Nicholson *et al.* (1986a, b) have emphasized seismicity patterns as evidence for conjugate faulting mechanisms of block rotations between and bounded by the San Andreas and San Jacinto fault zones from the Transverse Ranges south almost to Mexico, there is, nevertheless, much that we have yet to learn about how these "cross-faults" work. The cross-strike extent of the northeast-trending faults ruptured during these earthquakes is significantly greater than that of the aftershocks that lie beneath them. The number, complexity, and areal extent of these cross faults—in the epicentral region of the 1987 earthquakes and beyond—provide us with unanswered questions, as does their role in the significant volumetric deformation of the Pleistocene Brawley formation that lies just beneath the veneer of Coahuila sediments. Klinger and Rockwell (1989) show how slip variations along the Elmore Ranch fault are associated with progressive deformation of a small anticline caused by co-seismic flexural-slip mechanisms.

For the past 50 yrs, the southern and western portions of the Salton Depression traversed by the southern San Jacinto fault zone and the Imperial fault have been the most seismically active region of California (Fig. 2), at least at the $M \geqq 6$ level. Significant earthquakes rupturing the Imperial fault occurred in 1940 and 1979, with moment magnitudes M of 7.0 and 6.5, respectively. Along the southern San Jacinto fault zone, recent $M \geqq 6$ events are the 1954 Arroyo Salada ($M = 6.4$), the 1968 Borrego Mountain ($M = 6.5$), the 1942 Lower Borrego Valley ($M = 6.6$), and the 1987 Superstition Hills ($M = 6.6$) earthquakes; of these four earthquakes, only the 1968 and 1987 events have been positively associated with surface rupture.

The 1987 sequence of earthquakes has revitalized interest in the 1942 earthquake, which itself was followed by a $M_L = 5\frac{1}{2}$ "aftershock" $9\frac{1}{2}$ hrs later beneath the Salton Sea, some 30 km to the northeast. The studies of Hanks *et al.* (1975), Doser and Kanamori (1986), and Sanders *et al.* (1986) yield a consensus location of 33.0° N, 116.0° W for the 1942 main shock, exactly that given by Richter (1958), with a likely uncertainty of 5 to 10 km given the data available in the 1940's. In years gone by, most seismologists would have assumed that the 1942 earthquake occurred along the right-lateral, northwest-trending southern San Jacinto fault zone, leaving con-



Source Map: State Geologic Sheet co. 1965

FIG. 2. Locations of the Elmore Ranch ($M = 6.2$) and Superstition Hills ($M = 6.6$) earthquakes, shown as stars without dates, with respect to other $M \geqq 6$ earthquakes along the southern San Jacinto fault zone and the Imperial fault. The principal faults of the region have been digitized from the Santa Ana, Salton Sea, and San Diego-El Centro sheets of the Geologic Map of California, all more than 20 yr old. Surface ruptures are indicated as bold lines, other faults as lines of lesser thickness. EF, Elsinore fault; IF, Imperial fault; SJFZ, San Jacinto fault zone; SHF, Superstition Hills fault; SMF, Superstition Mountain fault. Note that the 1940, 1968, and 1979 earthquakes are indicated only by the surface faulting, not with epicentral locations. The higher elevations of the Superstition salient (Magistrale *et al.*, 1989) into former Lake Coahuila (dashed line) are lightly shaded.

siderable doubt as to whether a long-standing seismic gap existed along the southern San Jacinto fault zone after 1968 (*e.g.*, Thatcher *et al.*, 1975). If, however, the 1942 earthquake occurred along a northeast-trending, left-lateral structure, as perhaps is suggested by the aftershock locations of Doser and Kanamori (1986), one should conclude that the Superstition Hills/Superstition Mountain segment of the southern San Jacinto fault zone was indeed a long-standing seismic gap. Wesson and Nicholson (1987), in fact, identified the Superstition Hills/Superstition Mountain segment as a seismic gap and as a likely site for a $M \geqq 5.7$ earthquake in a 10-yr (11/86 to 11/96) seismicity forecast for California; the 1987 earthquakes, of course, support the Wesson and Nicholson (1987) identification. If the correct conclusion to be drawn from all this is that the 1942 earthquake indeed occurred on a northeast-trending, left-lateral structure, the size potential for earthquakes on such faults is at least $M = 6\frac{1}{2}$ to 7.

The paleoseismic investigations of Hudnut and Sieh (1989) on the Superstition Hills fault and Hudnut *et al.* (1989a) on the Elmore Ranch fault reveal that these faults were broken only once between ~1660 and 1987 (but not necessarily at the same time). If there is anything at all to the notion of average recurrence times, the 1942 earthquake is not likely to be the causative event. Because of the arid climate and controlled access due to military operations, the epicentral area abounds with delicate, faulting-controlled microgeomorphology, and such features have allowed Lindvall *et al.* (1989) to infer the existence of four and perhaps five prehistoric earthquakes.

Afterslip measurements, which continue to the time of this writing a year after the earthquakes, have figured prominently in the geologic investigations of the surface ruptures (Bilham, 1989; Boatwright *et al.*, 1989; Hudnut *et al.*, 1989b; McGill *et al.*, 1989; Sharp *et al.*, 1989; Sharp and Saxton *et al.*, 1989; Williams and Magistrale, 1989). Because of its long history of spasmodic creep/triggered-slip episodes known since 1951, with slip episodes having also occurred in 1965, 1968, 1979, 1981, and again in 1987, the Superstition Hills fault is exceptionally well-instrumented to observe these effects. In the case of the 1987 ruptures, afterslip and "co-seismic slip" (the slip accumulated 24 hrs after the second main shock) have contributed about equal amounts to the total right-lateral offset on the Superstition Hills fault; no afterslip, however, has been observed on any of the northeast-trending surface ruptures. With data collected from the deployment of three portable, digital creepmeters, Billham (1989) describes the amplitude/time/propagation history of individual creep events with a resolution that heretofore has not been available.

As is so often the case for $M \gtrsim 6$ earthquakes in this area, the 1987 earthquakes caused triggered slip along parts of the Coyote Creek fault that ruptured in 1968 (Hudnut and Clark, 1989; McGill *et al.*, 1989), along the Imperial fault which brokein 1940 and 1979 (McGill *et al.*, 1989, Sharp, 1989), and along the southern San Andreas fault at Salt Creek (McGill *et al.*, 1989). Both McGill *et al.* (1989) and Sharp (1989) report slip events on the Imperial fault that occurred 3 weeks before the 1987 earthquakes. McGill *et al.* (1989) also describe an equivocal slip event along the southern San Andreas fault in early November. There are, however, no reports of precursory slip on the Superstition Hills fault and the observations of Kahle *et al.* (1988) argue against such a happening. Moreover, Agnew and Wyatt (1989) report that strain and tilt recordings at the Piñon Flat Observatory, approximately 100 km distant from the two epicenters, require that precursory strain changes to either earthquake be no more than a small fraction of the coseismic strain changes.

Source mechanism studies of the Elmore Ranch and Superstition Hills earthquakes are presented by Bent *et al.* (1989), Frankel and Wennerberg (1989), and Sipkin (1989), using close-in strong-motion accelerograms, regional seismograms, and teleseismic data. The Elmore Ranch earthquake is a fairly simple event, for which the seismic moment is $M_o = 2.3$ to 2.7×10^{25} dyne-cm. All three of these investigations find the Superstition Hills earthquake to be a multiple, complex event. Estimates of its M_o from teleseismic data are 10 to 11×10^{25} dyne-cm, factors of 2 to 3 greater than those determined from the strain/tilt data at Piñon Flat (Agnew and Wyatt, 1989) and a factor of 10 larger than the M_o expressed at high frequency (~1 Hz) in the close-in strong-motion accelerograms (Frankel and Wennerberg, 1989). Frankel and Wennerberg, from their analysis of close-in data, find three subevents, all located within 8 km of each other along the northern reaches of the Superstition Hills fault. Evidently, the southeastern two thirds of the Superstition Hills fault, where there were relatively few aftershocks as well, contributed little to the high-frequency ($f \gtrsim 0.5$ Hz) energy radiated by the Superstition Hills earthquake.

Readers of this special issue may wish to take note of important data sets that have been published elsewhere, including unprocessed and processed strong-motion data (Porcella *et al.*, 1987; Huang *et al.*, 1987), a very substantial set of aftershock seismograms recorded digitally over a broad magnitude range (Andrews *et al.*, 1988), and the first simultaneous recordings of pore pressure and uphole/downhole strong ground motion at a site that liquefied massively during the second main shock—but not the first (Holzer *et al.*, 1989). Kahle *et al.* (1988) provide additional details of surface faulting for these earthquakes.

Several matters concerning precursory phenomena and earthquake prediction are worth recounting in the context of the 1987 earthquakes. From long-term to short-term, the narrative begins with the 10-yr forecast of Wesson and Nicholson, discussed above, that the Superstition Hills/Superstition Mountain segment of the southern San Jacinto fault zone was a likely site for a $M \geqq 5.7$ earthquake. H. Kanamori (personal comm.) had noted that this fault segment was aseismic for the 6 months preceding the North Palm Springs earthquake (8 July 1986; $M = 5.9$), but was the most seismic segment of the San Jacinto fault zone for the next 6 months. The aseismic slip along the Imperial Fault described by McGill *et al.* (1989) and Sharp (1989) 3 weeks before the 1987 earthquakes may be a precursor, but this will be hard if not impossible to establish, èspecially in view of the absence of such effects along the Superstition Hills fault.

One of the more interesting seismological vignettes of recent times concerns the Working Group on California Earthquake Probabilities, which on 23 November 1987 was meeting in Menlo Park and deliberating what was known about the Superstition Hills segment of the San Jacinto fault zone. Literally 4 hrs before the time of the Elmore Ranch earthquake, the Working Group finally decided that insufficient evidence was available to warrant a probability estimate for this particular fault segment. The Working Group (1988) went on to say, with words well worth remembering,

> Ironically, 30 km of the Superstition Hills fault ruptured in a magnitude 6.6 event the next day. While validating our choice of segment, this experience well illustrates a major problem in attempting probabilistic long-term earthquake prediction for active faults in California. While knowledge of particular segments may often be less than would justify a quantitative assessment, our ignorance does not imply the fault is less hazardous. The 1987 Superstition Hills earthquake shows that many fault segments deserve close attention, whether or not quantitative hazard assessments can be narrowly constrained (or even established) by the data available.

Finally, the Elmore Ranch earthquake was itself precursory to the Superstition Hills earthquake by 12 hrs, and had we been wise enough, we might have predicted the second and larger event. The possibility that the Elmore Ranch earthquake might instead trigger a major earthquake on the southernmost segment of the San Andreas fault northeast of the Salton Sea, which has not experienced a large earthquake for more than 300 yr (Sieh and Williams, 1989), did, in fact, occupy scientists and various state and federal officials in Menlo Park, Pasadena, Sacramento, and Washington, D.C., well into the small hours of 24 November—after it became clear that aftershocks of the Elmore Ranch earthquake had a northeast-trending alignment. Their concern and rational were well placed; just as the Elmore Ranch earthquake decreased the normal stress across the Superstition Hills fault southeast of their intersection, a mirror-image relationship exists on the San Andreas fault northwest of the intersection between it and the Elmore Ranch fault. Indeed, when the second, larger event rudely awakened people throughout southern California, many of us momentarily assumed the worst and that a major San Andreas earthquake was in the making. As things turned out, this was not the case, probably because the Elmore Ranch earthquake was located much closer to the Superstition Hills fault than to the San Andreas fault. It is, of course, our good fortune that this potentially much larger earthquake did not occur on the San Andreas fault—this time. Perhaps more importantly, the 1987 earthquakes have revealed to us important new processes by which we may anticipate and perhaps predict the earthquake next time.

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