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SEISMIC DEFORMATION ALONG THE SOUTHERN SAN ANDREAS FAULT:

Implications for Rotational Block Tectonics.

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Abstract

The pattern of microseismicity in southern California indicates that much of the activity is presently occurring on secondary fault structures. Near the intersection of the San Jacinto and San Andreas faults, these secondary structures exhibit predominantly left-lateral strike-slip motion, and, in conjunction with both normal and reverse faulting earthquakes, suggests a series of small crustal blocks undergoing contemporary clockwise rotation as a result of regional right-lateral shear. Other left-lateral faults have been identified in adjacent areas from geologic and seismologic data. Many of these structures predate the modern San Andreas system and may control the pattern of strain accumulation in southern California. Thus, although the total slip along these secondary structures is small, they may affect where large earthquakes nucleate and the characteristic length of large earthquake ruptures. A complete description of what these structures are, and how they interact, may prove critical to any fundamental understanding of the earthquake process and any realistic assessment of the regional seismic hazard.

Introduction

One of the more enigmatic features of southern California seismicity is the lack of correlation between present activity and the major through-going faults [Allen *et al.*, 1965; Allen, 1981]. This is particularly true for those segments responsible for the largest earthquakes (*e.g.*, the 1857 fault rupture), as well as for the southern San Andreas fault; even though these faults are known to be accumulating strain at the rate of centimeters per year. Only the San Jacinto fault, Brawley fault, and the creeping section of the San Andreas are well defined on the basis of present seismicity. There do appear, however, to be many earthquakes on secondary structures, many of which are oriented orthogonal to the strikes of the major faults [Nicholson *et al.*, 1984]. Considering the abundance of this secondary activity, a framework is needed in order to understand the structures at depth responsible for the earthquakes and to determine what relation the present pattern has to the seismic behavior of the major fault strands.

We therefore began a systematic examination of the geologic and geophysical evidence in an attempt to resolve the exact nature of some of these active secondary structures. The procedure was to invert arrival-time data from microearthquakes for local velocity structure and accurate earthquake hypocenters. Focal mechanism solutions were then analyzed for internal consistency with the orientation of the resulting structural elements defined on the basis of the hypocenter alignments. This permitted a qualitative description of the overall kinematic pattern controlling fault interaction and the discrimination between various tectonic models for the contemporary deformation of southern California [*e.g.*, Bird and Rosenstock, 1984; Luyendyk *et al.*, 1985; Weldon and

Humphreys, 1985].

Our initial study involved only a small segment of the San Andreas, where the fault begins to make its "big bend". This segment lies between the San Bernardino Mountains and the San Jacinto Mountains, and includes San Gorgonio Pass (SGP) and the intersection of the San Andreas with the San Jacinto fault (Fig. 1). It is an area characterized by a complex surface geology, intersecting right- and left-lateral faults, high topography as a result of recent uplift, and one of the highest levels of deep seismicity (>20 km) anywhere along the entire San Andreas [Allen, 1957; Meisling, 1984; Corbett and Hearn, 1981]. Microearthquakes show a wide range of focal mechanism solutions [Green, 1983], and waveforms on seismograms suggest high stress drops [Frankel and Kanamori, 1983]. These indicators imply a region of high strength under unusually high stress [*e.g.*, Sibson, 1984], and as a consequence, one of the highest potentials for initiating a large earthquake rupture. Failure of this segment could then result in an earthquake that would not stop until it stretched from as far north as Palmdale to as far south as the Salton Sea (Fig. 1, C-D).

Summary of Results

Using data supplied by the southern California seismic network, we found that although this area is unusually seismogenic, very few earthquakes were occurring in the upper 5 km, or could be directly associated with any of the major through-going faults. Instead, an active system of relatively short left-lateral faults striking north-east to east-west was identified for earthquakes between focal depths of 5 and 10-12 km. This pattern of deformation, in conjunction with an unusual set of both normal and reverse faulting earthquakes, suggested a series of small rigid blocks undergoing clockwise rotation as a result of regional right-lateral shear (Fig. 2). The normal and reverse faulting earthquakes represent the corners of the blocks rotating into or away from the sides of the major bounding faults. If valid, this is the first study to identify blocks undergoing contemporary rotations - rotations that are more commonly identified on the basis of paleomagnetic work and only for much longer time scales.

Other earthquakes that show left-lateral slip on north-east trending structures include several events along sub-parallel features located west of the San Jacinto fault and first identified by Hadley and Combs [1974] (focal mechanism A in Fig. 2). Each of these structures, as well as the northeast trend of earthquakes located under the town of San Bernardino (focal mechanism H in Fig. 2), corresponds to a known vertical aquiclude affecting ground-water migration in the sediments of the San Bernardino valley [Dutcher and Garrett, 1963]. Where these structures intersect the San Jacinto and San Andreas faults, hot springs and thermal wells are evident that are relatively rare for other sections of the San Andreas system [Jennings, 1975]. Thus, motion along these presumed fault structures must have been sufficient to generate a clay fault gouge capable of acting as an effective water barrier. This implies that although these fault segments are relatively short, they may still constitute a significant seismic hazard to the local population. In fact, intensity data suggests that the 1923 magnitude 6¼ earthquake may have actually occurred along the fault segment that parallels the Santa Ana river (focal mechanism G in Fig. 2) rather than along the San Jacinto fault where it is presumed to be located [Laughlin *et al.*, 1923; Toppozada *et al.*, 1982]. If this earthquake did in fact occur along one of these secondary structures, then the northern section of the San Jacinto fault has not experienced a large earthquake since 1899, and so is more highly susceptible to an earthquake rupture in the near future.

Further east, between the Banning and Mission Creek faults, another set of earthquakes occur that also appear to exhibit left-lateral slip on north-east trending features (Fig. 3). These events align along sub-parallel trends that dip steeply to the south and agree quite well with the orientation of the north-east striking nodal plane seen in the composite focal mechanism solution. Slip along the *en echelon* northeast planes would be left-lateral, but with a larger component of reverse faulting. This type of deformation matches the long-term history of the Pinto Mountain and Morrango Valley faults with which these events align, and may indicate that slip along these features may have at one time extended across the Mission Creek fault. Such high-angle reverse faulting has been previously observed in the shallow surface sediments of San Gorgonio Pass [Allen, 1957], although most of the deformation more closely corresponds to slip along right-lateral strike-slip and shallow-angle thrust faults [Matti and Morton, 1983].

An interesting feature of all this seismicity is that those earthquakes exhibiting left-lateral slip on northeast trends all occur at depths less than ≈10 km (see cross section Fig. 3); suggesting that what ever mechanism is controlling this behavior, it is primarily restricted to shallow depths. Furthermore, if these left-lateral faults are the result of small crustal blocks that are currently rotating then this presupposes a detachment surface at depth, decoupling the blocks, and allowing rotational movement. Regional mid-crustal detachments or ductile shear zones have been suggested based on the occurrence of large earthquakes at depth with shallow-angle nodal planes [Webb and Kanamori, 1985], by the regional pattern of teleseismic travel-time residuals [Hadley and Kanamori, 1977], and by the finite elastic thickness of the upper crust [Turcott *et al.*, 1984]. If a detachment is present, then the possibility exists that the geology and/or the deformation observed at the surface is different from the deformation at depth.

In fact the microearthquakes below 10-12 km are distinctly different from those above. At greater depths, regional north-south shortening resulting from the collision of the San Jacinto Mountains with the San Bernardino Mountains, was found to be accommodated by a combination of strike-slip faults interbedded between a series of subparallel shallow-angle thrust faults dipping to the north (Fig. 4). Determinations of velocity structure from the earthquake arrival times also indicate a possible low-velocity layer at about 10 km depth under the San Bernardino Mountains but not under the San Jacinto Mountains [Nicholson and Simpson, 1985]. This is about the same depth as the transition between the block rotations and the deeper deformation, and suggests the overthrust San Bernardino Mountains are allochthonous. Regional gravity data and the distribution of P_g velocities also support this interpretation [Hearn and Clayton, 1984].

Discussion and Conclusions

If these results have applications elsewhere along the San Andreas system, it provides several new concepts for understanding the kinematic behavior and fault tectonics for southern California. Shallow-angle structures like detachments need to be examined, and in the analysis of regional strain data rotations must be considered. The elastc behavior of the crust may thus strongly dependent on the nature of any pre-existing fabric and the depth to either a decollment or ductile shear zone. More important, the pattern of deformation presently observed during the interseismic period differs from the type of deformation expected to take place during a large earthquake. Current seismicity cannot then be used to extrapolate the effects of a large event on various segments of the San Andreas, since large earthquakes are the result of right-lateral slip along major faults, whereas much of the present activity is on secondary faults, some of which are accommodating left-lateral motion as a result of block rotation.

As blocks rotate, the level of normal stress may increase or decrease along strike as block corners rotate into or away from the sides of the major bounding faults. This increased or decreased level of normal stress may account for the alternating pattern of high and low levels of earthquake activity seen along strike of some of the major fault strands (*e.g.*, the San Jacinto fault). Block dimensions may also control the characteristic size of earthquake ruptures. An example would be the northeast trend of left-lateral earthquakes located near the Mission Creek branch of the southern San Andreas and just south of the Pinto Mountain fault [Williams *et al.*, 1984]. These events defined a series of *en echelon* faults and separate the aftershocks of the 1947 Morrango Valley earthquake from those of the 1948 Desert Hot Springs event. Where large earthquakes nucleate may also be controlled by where blocks come together, and faults intersect [*e.g.*, Jones, 1984]. The result is often a cross-pattern of either foreshocks or aftershocks, as in the case of the Borrego Mountain earthquake of 1968, the Homestead sequence of 1979, or the Manix earthquake of 1947. The regional pattern of strains and tilts is also likely to reflect the block nature of the crust [Bilham and Beavan, 1979].

Detailed mapping of the geologic structures in southern California reveal a number of shallow-angle thrust surfaces and left-lateral faults much like those suggested by the seismicity [Engel and Schultejann, 1984]. Many of these structures pre-date the development of the modern San Andreas system. If these older structures are effectively segmenting southern California into discrete crustal blocks, then efforts must be made to determine the extent to which these blocks are involved in the overall seismic deformation of southern California.

The seismic data examined so far require neither large rotations nor large left-lateral displacements, but if rotations persist and eventually accumulate with time, then large deflections from the paleomagnetic pole would be expected. Luyendyk *et al.* [1985] summarize most of the available paleomagnetic data for southern California. They show that for large parts of southern California large clockwise deflections are in fact observed in deposits of Neogene and Quarternary age (Fig. 5). Previous models used to explain these observations typically invoke large rotations of large rigid blocks. If however these measurements are the result of simple shear involving only small crustal blocks, wedges, or slices, then both the paleomagnetic data are satisfied, and many of the geologic contradictions caused by large rigid block rotation are avoided. These data thus imply that large rotations induced by tectonic shear do occur and are closely coupled to the wrench fault environment of the San Andreas system.

How long this particular pattern of kinematic behavior will persist in time is uncertain. The present pattern may only characterize the interseismic period and may change as this region prepares to accommodate large earthquake ruptures. Should this change be systematic, then there is a higher probability of identifying the precursory change and thereby predicting the impending large earthquake and the occurrence of large right-lateral displacements.

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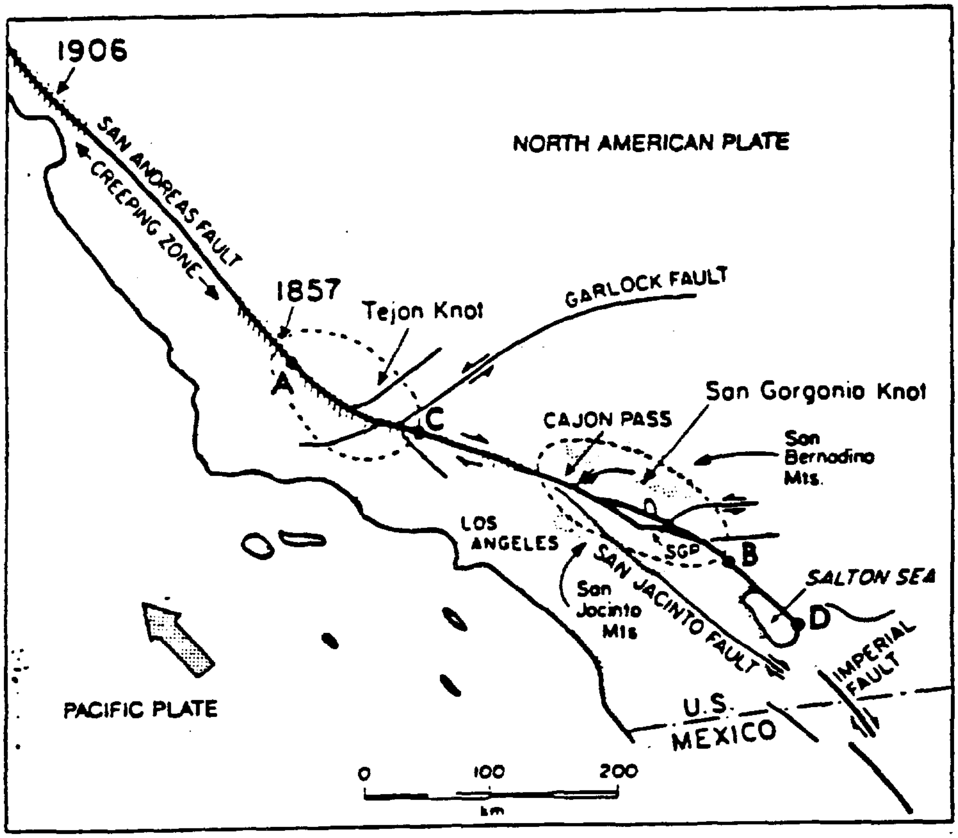


Figure 1. Major faults and earthquake ruptures in Southern California. A-B represents the "big bend" section of the San Andreas fault. The western end (Tejon Knot) broke in 1857 and ruptured as far south as Cajon Pass. The eastern end (San Gorgonio Knot) has not broken since the early 1700's and has a probable repeat time of 300 years. Should this section fail all at once, the potential rupture length of the resulting great earthquake could extend from C to D.

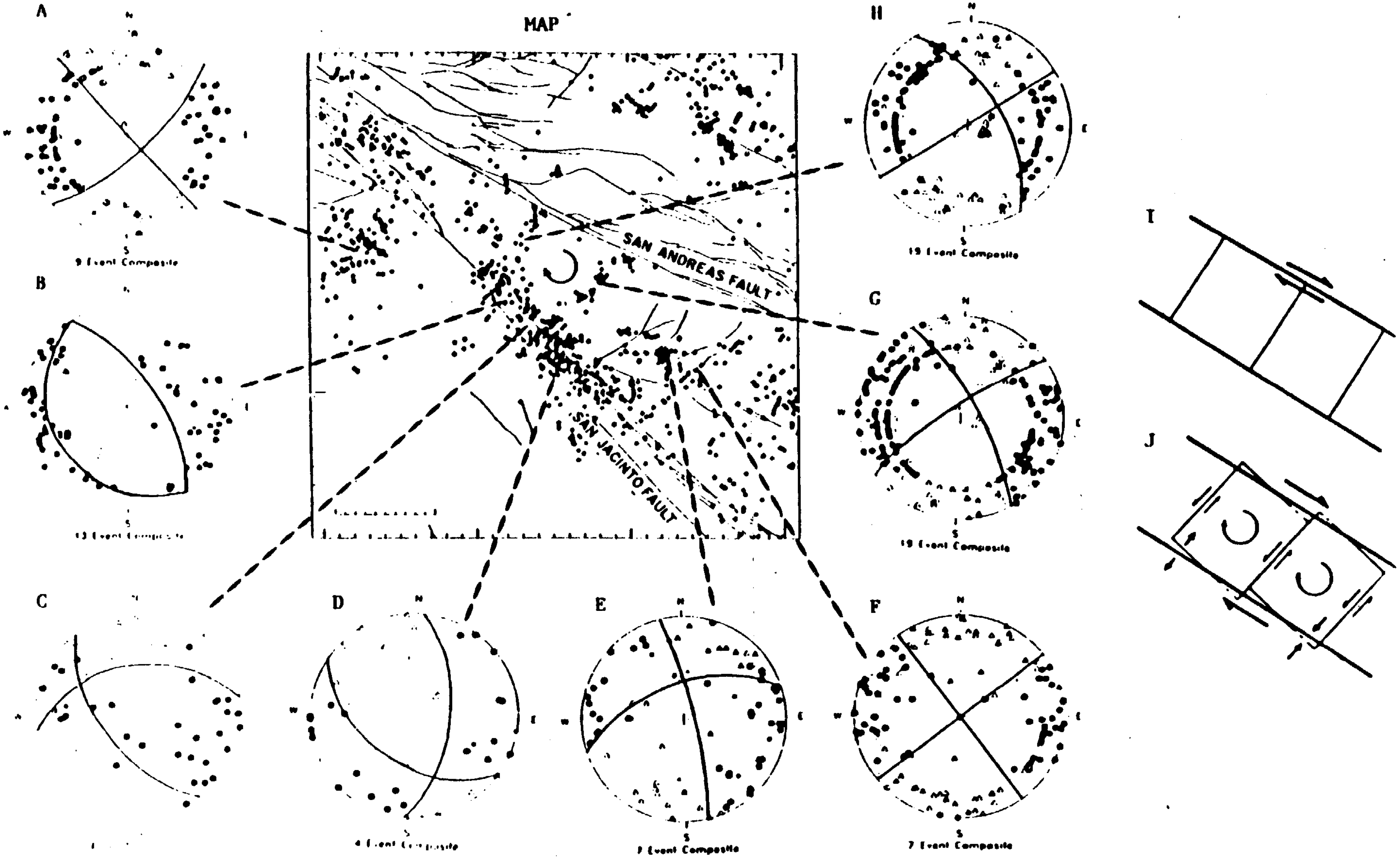
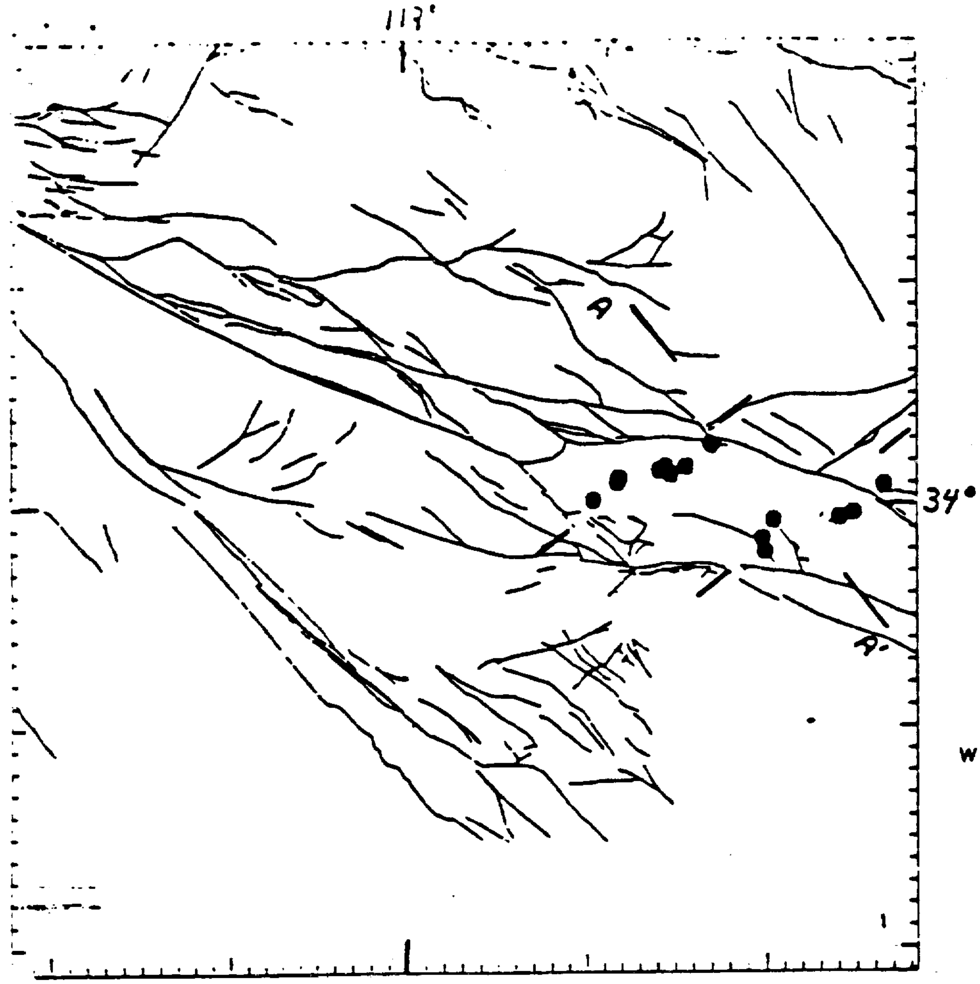
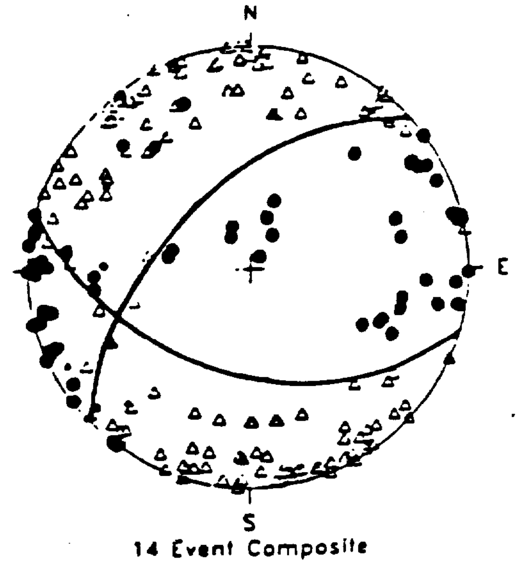


Figure 2. Shallow seismicity used to define rotating blocks near the intersection of the San Andreas and San Jacinto faults - see map. During a large earthquake right-lateral strike-slip motion (I) occurs on one of the major bounding faults; however, during the inter-seismic period, the major faults become locked causing small blocks in between to rotate (J). This produces a pattern of northeast striking left-lateral faults (E-H), between which alternating groups of normal (B&D), and reverse (C) faulting earthquakes occur that match the particular pattern predicted by the model (compare J with map). Focal mechanism diagrams (A-H) are composite upper hemisphere projections; solid symbols are compressions, open symbols are dilatations. Composite A (upper left) represents a set of sub-parallel left-lateral faults previously identified by Hadley and Combs (1974).





14 Event Composite

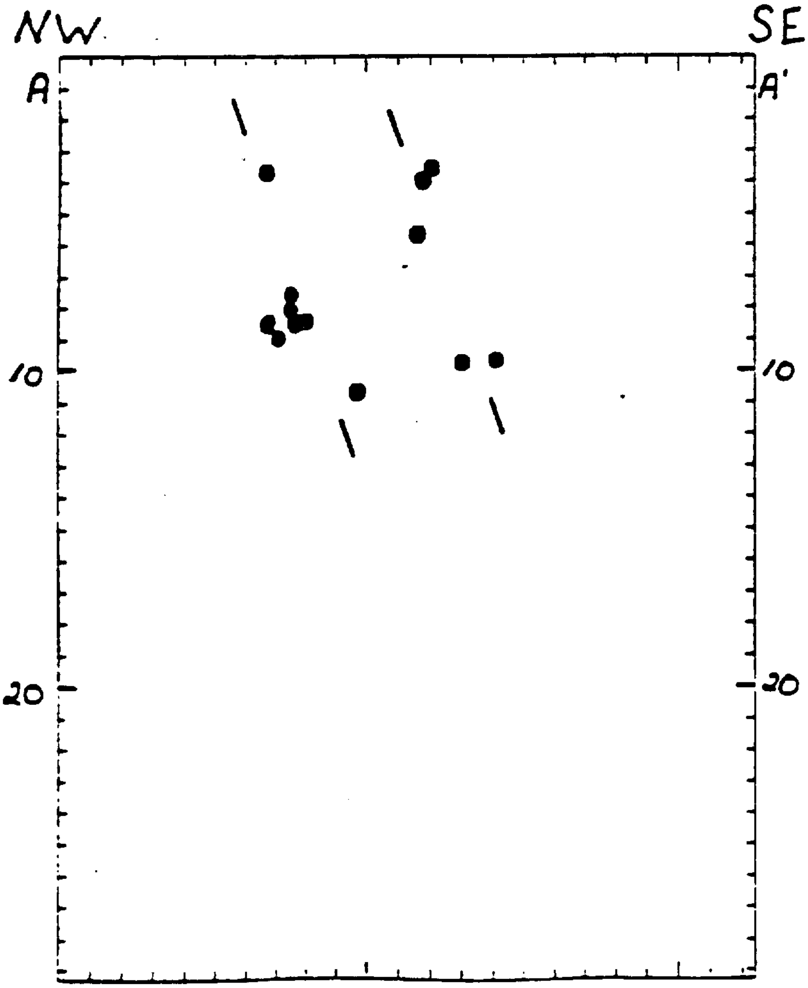


Fig. 3. Map and cross section of events between the Mission Creek and Banning Faults. These earthquakes align along planes that dip steeply to the south and exhibit compressional left-lateral strike-slip motion along northeast oriented nodal planes.

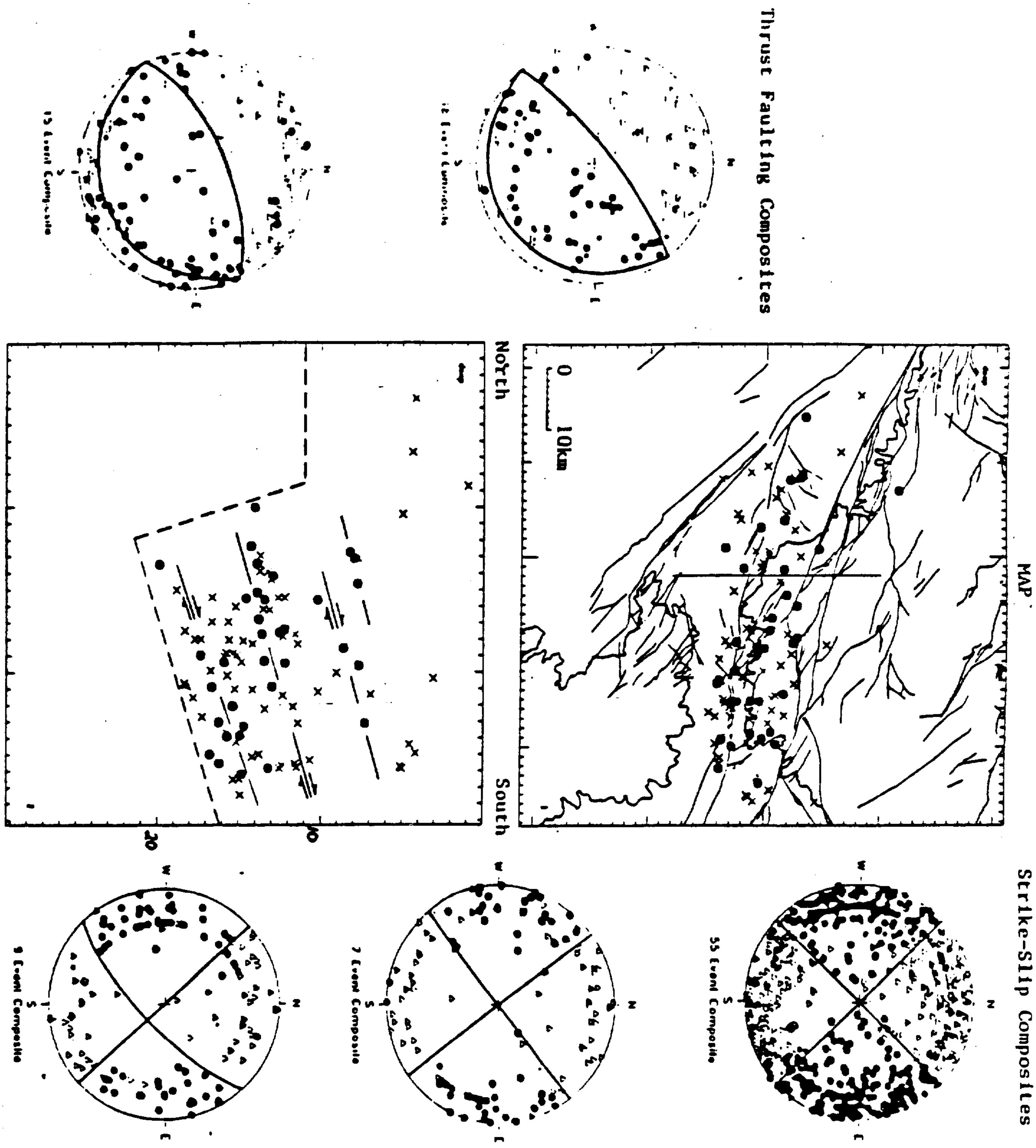


Figure 4. Map and cross section of the predominately deeper strike-slip (X's) and shallow-angle thrust events (solid circles) near San Gorgonio Pass. The thrust earthquakes define a series of planes that dip to the north and parallel the shallow-dipping interface that defines the base of the seismogenic zone (dashed line) and match the shallow-angle nodal plane seen in the composite focal mechanisms shown at left. The seismicity shows a wedge-shaped volume internally deforming as a result of north-south shortening between the San Bernardino Mts to the north and the San Jacinto Mts to the south. Contours are elevations above 3,000 feet.

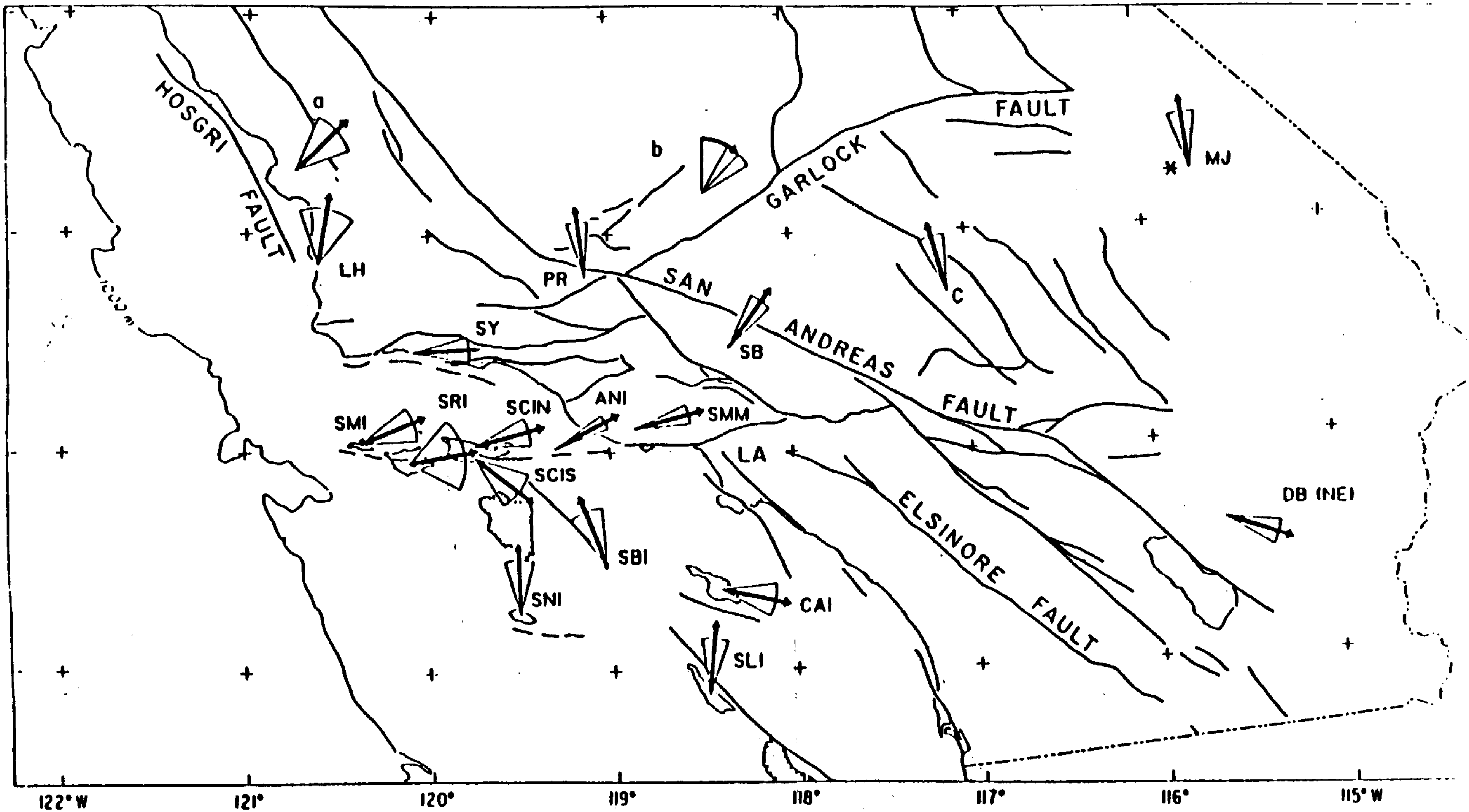


Figure 5. Paleomagnetic declinations measured in Neogene age rocks (about 13 m.y.) at sites throughout southern California. The mean declination at the site is shown along with the 95% confidence limit. Faults are from Jennings (1975). See Luyendyk et al. (1985) for more specific information and site keys.