

SEISMIC EVIDENCE FOR CONJUGATE SLIP AND
BLOCK ROTATION WITHIN THE SAN ANDREAS
FAULT SYSTEM, SOUTHERN CALIFORNIA

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Abstract. The pattern of seismicity in southern California indicates that much of the activity is presently occurring on secondary structures, several of which are oriented nearly orthogonal to the strikes of the major through-going faults. Slip along these secondary transverse features is predominantly left-lateral and is consistent with the reactivation of conjugate faults by the current regional stress field. Near the intersection of the San Jacinto and San Andreas faults, however, these active left-lateral faults appear to define a set of small crustal blocks, which in conjunction with both normal and reverse faulting earthquakes, suggests contemporary clockwise rotation as a result of regional right-lateral shear. Other left-lateral faults representing additional rotating block systems are 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. Geodetic and paleomagnetic evidence confirm that block rotation by strike-slip faulting is nearly ubiquitous, particularly in areas where shear is distributed, and that it accommodates both short-term elastic and long-term nonelastic strain. A rotating block model accounts for a number of structural styles characteristic of strike-slip deformation in California, including: variable slip rates and alternating transensional and transpressional features observed along

strike of major wrench faults; domains of evenly-spaced antithetic faults that terminate against major fault boundaries; continued development of bends in faults with large lateral displacements; anomalous focal mechanisms; and differential uplift in areas otherwise expected to experience extension and subsidence. Since block rotation requires a detachment surface at depth to permit rotational movement, low-angle structures like detachments, of either local or regional extent, may be involved in the contemporary strike-slip deformation of southern California. A block nature of the crust also implies that not only will strains be inhomogeneous and likely concentrated along edge-bounding faults, but that local stress orientations will largely be responding to local kinematic constraints of block rotation and fault interaction. This behavior, coupled with the presence of possible regional detachments, accounts for some of the precursory changes observed at considerable distances prior to large earthquakes and the triggering of seismicity or slip on nearby faults or around adjacent block edges. Although fault displacements along secondary structures associated with block rotations remain small, they may still influence the nucleation and the characteristic rupture length of large earthquakes. A more 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.

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Paper number 6T0103.
0278-7407/86/006T-0103\$10.00

INTRODUCTION

Since the advent of plate tectonic theory and the recognition of the San Andreas fault system as a major transform plate boundary, it has often been assumed that strike-slip earthquakes in the vicinity of the San Andreas fault necessarily reflect right-lateral motion on parallel or nearly parallel northwest-oriented wrench faults. This as-

sumption can prove misleading, as demonstrated by the occurrence of the 1980 Eureka earthquake ($M_S=7.2$, $M_w=7.3$). Prior to the earthquake, strike-slip events in the Gorda basin off Cape Mendocino were presumed to represent right-lateral slip on northwest-oriented nodal planes, primarily because of the proximity of the earthquakes to the San Andreas wrench fault environment [Tobin and Sykes, 1968; Bolt et al., 1968; Seeber et al., 1970]. Slip during the 1980 earthquake, however, was left-lateral along what had previously been inferred to be the northeast-oriented auxiliary plane from earlier focal mechanisms [Smith et al., 1981; Eaton, 1981]. This type of deformation is consistent with the breakup and tectonic rotation of the Gorda basin as it subducts along the North American plate margin. The shear-induced rotation and internal deformation of the Gorda plate are accommodated by left slip along preexisting zones of weakness developed at the Gorda spreading ridge. These secondary faults are progressively rotated and correlate with well-developed topographic scarps and magnetic lineations identified by Silver [1971] based on bathymetry, seismic reflection data, and regional magnetic surveys.

In this paper, we show that adjacent to major strands of the San Andreas fault system, there are also examples of contemporary seismic activity on northeast-oriented left-lateral faults. Because many of these faults are oriented at relatively high angles to the general trend of the San Andreas system, and because the sense of slip is in the opposite sense, we will call these faults conjugate and the slip antithetic. These active secondary features are most prominent in areas where major right-lateral faults splay, bend or overlap; and may reflect the primary mechanism whereby slip is transferred across major fault offsets and other fault discontinuities. These structures can be interpreted as representing a system of conjugate faults accommodating distributed right-lateral shear by small-scale block rotation, similar to the observed deformation of the Gorda basin. The advantage of this model is that it can account for a number of unusual features observed in the neotectonic deformation of southern California, including: variable slip rates and the presence of alternating transensional and transpressional features along strike of major wrench faults; the continued development of bends in faults with large right-lateral displacements; anomalous or rotated focal mechanisms; and the formation of time-dependent asperities that effect the rupture behavior of large earthquakes. Thus, even though the actual seismic energy released along these secondary faults is small, they may play an unusually important role in controlling the seismic behavior of major faults, and the location of where large earthquakes nucleate.

SEISMICITY

One of the more puzzling characteristics of earthquakes in southern California is that few of the many small to moderate size earthquakes that have occurred correlate with major mapped surface faults [Richter, 1958; Allen et al., 1965; Brune and Allen, 1967; 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 [Leitner et al., 1979], even though these sections are known to be accumulating strain at the rate of centimeters per year. In southern California, only the San Jacinto fault, the Brawley fault, and the northern part of the Imperial fault are well defined on the basis of present seismicity. Figure 1 is a map of well-located earthquake epicenters in southern California with horizontal errors in location of less than 2.5 km. The data represent 8 years of continuous monitoring by the California Institute of Technology (Caltech) and the U.S. Geological Survey since augmentation of the regional network in 1975. Figure 1 clearly shows how little of the present activity can be directly related to slip along the San Andreas fault zone. There do appear, however, to be many earthquakes on secondary structures, several of which are oriented nearly orthogonal to the strikes of the major through-going faults [Nicholson et al., 1984]. Other earthquakes appear to define short fault segments oriented subparallel to the dominant regional fault pattern. Considering the abundance of this secondary activity, a framework is needed in order to understand the structures at depth responsible for these earthquakes and to determine what relation the present pattern has to the seismic behavior of the major mapped surface faults.

We therefore began a systematic examination of the geologic and geophysical evidence in an attempt to resolve the nature of some of these active secondary features. The procedure was to use local velocity structure to invert arrival-time data from microearthquakes for accurate earthquake hypocenters. Focal mechanism solutions were determined and analyzed for internal consistency with the resulting structural elements defined on the basis of hypocentral alignments. This permitted the orientation and sense of slip of active subsurface faults to be identified. The results were then combined with other data, including geology, paleomagnetism, geodesy and model studies, in an attempt to provide 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.

SUMMARY OF PREVIOUS RESULTS

Our initial study area involved a small segment of the San Andreas, corresponding to where the fault begins to make its "big bend" in southern California. This segment lies between the San Bernardino Mountains and the San Jacinto Mountains, and includes San Gorgonio Pass and the intersection of the San Andreas with the San Jacinto fault (Figure 1, inset A).

Shallow Seismicity and Block Rotation

Using data supplied by Caltech from the southern California network, we found that although this area is unusually seismogenic, few earthquakes are occurring in the upper 5 km, or can be directly related to right slip along any of the major through-going faults [Nicholson et al., 1986]. Instead, an active system of relatively short

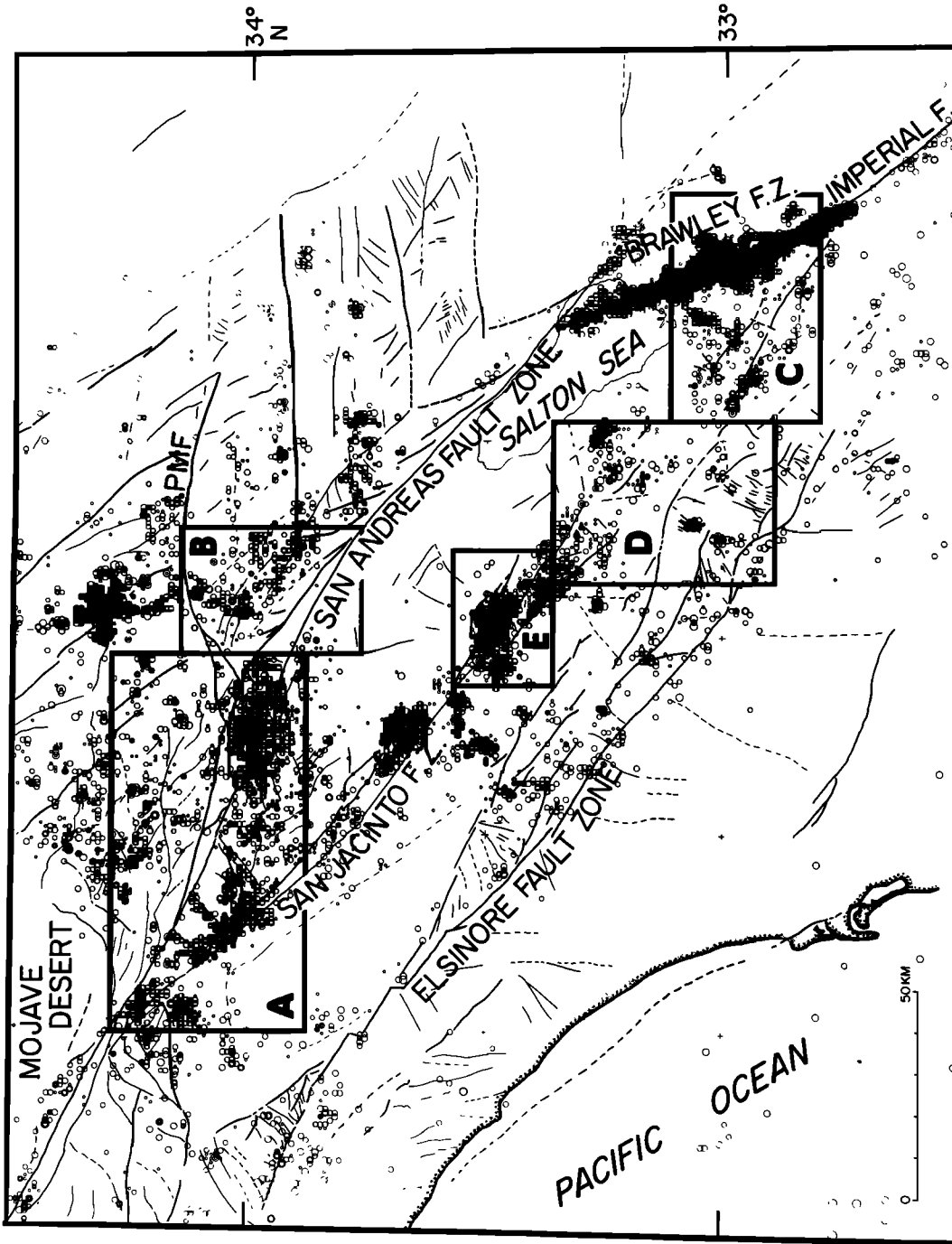


Fig. 1. Seismicity in southern California from 1975 to 1983. Only epicenters with horizontal errors in location of less than 2.5 km from the CIT-USGS catalog are shown. Faults are primarily from Jennings *et al.* [1975]. Dashed faults are inferred from seismicity or topography. Earthquakes within boxed areas are examined in detail and shown in subsequent figures. PMF = Pinto Mountain fault.

left-lateral faults striking northeast was identified for earthquakes between focal depths of 5 and 10–12 km (Figure 2). This pattern of deformation, in conjunction with an unusual set of both normal and reverse faulting earthquakes, was interpreted as a series of small rigid blocks undergoing clockwise rotation as a result of regional right-lateral shear. The normal and reverse faulting earthquakes are thought to represent the corners of the blocks rotating into or away from the sides of the major bounding faults, in a manner originally proposed by *Dibblee* [1977]. If valid, this is the first study to identify blocks undergoing contemporary rotations, rotations that have been more commonly identified on the basis of paleomagnetic evidence and only for much longer time scales.

Corroboration of Active Subsurface Faults

Other earthquakes that show left slip on conjugate northeast-trending structures include several events along subparallel planar features located west of the San Jacinto fault, and first identified by *Hadley and Combs* [1974] (focal mechanism *A* in Figure 2). Each of these subsurface features, as well as the northeast trend of earthquakes located under the town of San Bernardino (focal mechanism *H* in Figure 2), corresponds to a known vertical aquiclude obstructing ground water migration in the sediments of the San Bernardino valley [*Dutcher and Garrett*, 1963; *J. Matti*, personal communication, 1983]. Oblique displacement must thus have been sufficient to generate either an offset in permeable layers or a clay fault gouge capable of acting as an effective water barrier.

Further confirmation that such subsurface faults are active and may constitute a significant seismic hazard to the local population is provided by intensity data from the 1923 magnitude 6¼ earthquake [*Laughlin et al.*, 1923]. These felt reports suggest that this earthquake more likely occurred along the middle fault segment that parallels the Santa Ana river (focal mechanism *G* in Figure 2), rather than along the San Jacinto fault where it has been presumed to be located [*Topozada et al.*, 1982]. If this earthquake did in fact occur along one of these northeast-oriented left-lateral faults, then the northern section of the San Jacinto fault has not experienced a major earthquake since 1899, and so is more likely to experience a large earthquake rupture in the next few decades [*Sykes and Nishenko*, 1984]. Also, removal of the 1923 event from consideration as slip along the San Jacinto fault increases the characteristic size of large earthquakes on the northern San Jacinto to a magnitude of nearly 6.8, consistent with the longer recurrence interval that would be estimated if the 1923 event did indeed occur on a subsidiary fault.

Coincidentally, a moderate size earthquake ($M_L = 4.9-5.0$) occurred on October 2, 1985, at the intersection of this middle fault section (*G*, Figure 2) and the San Jacinto fault. It was widely felt throughout southern California and was the largest earthquake in this region since 1939. Its focal mechanism is consistent with left slip along a northeast nodal plane that parallels the previously inferred northeast subsurface structure. The other nodal plane, however, is more than 20° off from the strike of the

San Jacinto fault [*R. Norris*, written communication, 1985].

Farther east, between the Banning and Mill Creek faults, another set of earthquakes also appears to exhibit left slip on northeast-trending planar structures (Figure 3). These events align along subparallel features that dip steeply to the south and agree with the orientation of the northeast-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. Such high-angle faulting has previously been observed in the shallow sediments of San Geronio Pass [*Allen*, 1957], although most of the surface deformation more closely corresponds to slip along a combination of northwest-oriented right-slip faults and northward-dipping low-angle thrust faults [*Matti et al.*, 1985].

Deep Seismicity and a Regional Decollement

An interesting feature of much of this seismicity is that all the earthquakes exhibiting left slip on northeast trends occur at depths of less than ≈10 km (e.g., Figure 3). If the left-lateral faults are related to block rotation, they must be detached from the unrotated crust at depth [*Terres and Sylvester*, 1981]. In California, regional midcrustal detachments or ductile shear zones have been previously suggested based on: the occurrence at depth of large earthquakes with low-angle nodal planes which parallel the shallow-dipping base of the seismogenic zone [*Webb and Kanamori*, 1985]; by the finite elastic thickness of the upper crust [*Turcotte et al.*, 1984]; and by the areal heat flow and limited depth of faulting observed in large strike-slip earthquakes [*Prescott and Nur*, 1981]. Deep seismic reflection profiles also exhibit low-angle reflecting surfaces under the Mojave Desert, some of which outcrop along known thrust faults [*Cheadle et al.*, 1986]. If a detachment is present, contemporary deformation observed near the surface may be significantly different from the deformation observed at depth.

In fact, the microearthquakes below 10–12 km are distinctly different from those above. *Nicholson et al.* [1986] found that, at greater depths, regional north-south shortening and east-west extension resulting from the collision of the San Jacinto Mountains with the San Bernardino Mountains, is being accommodated by a combination of high-angle strike-slip faults and a series of subparallel low-angle thrust faults that dip to the north (Figure 4). Determinations of velocity structure from 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 inferred transition between the block rotations and the deeper deformation, and corresponds to the lower limit of seismicity that extends north into the Mojave region [*Corbett and Hearn*, 1981; *Webb and Kanamori*, 1985].

Palinspastic reconstructions suggest that the San Bernardino Mountains were repeatedly overthrust to the south and west, and are now undergoing rapid uplift and tilting to the north [*Meisling and Weldon*, 1986]. This deforma-

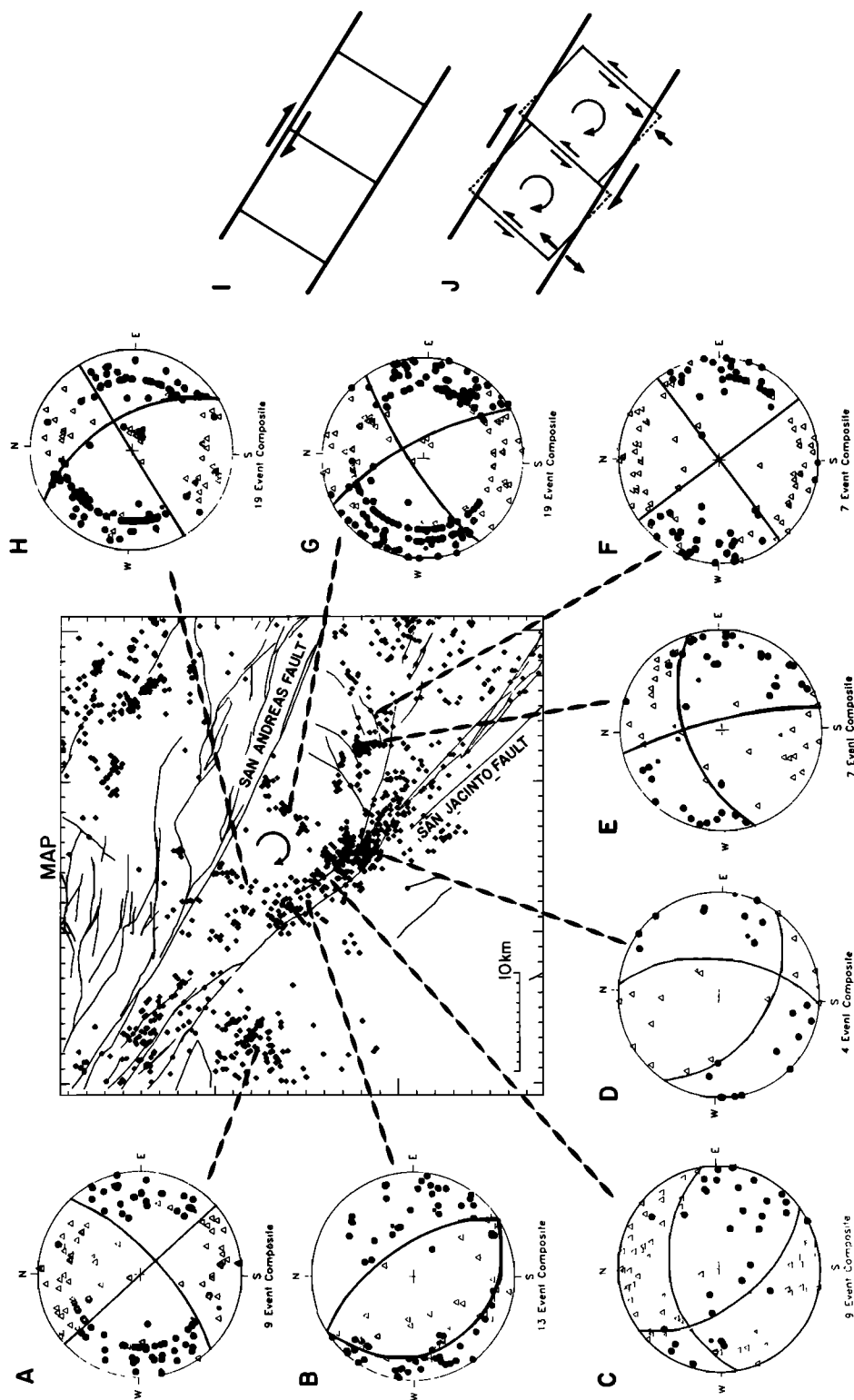


Fig. 2. Shallow seismicity used to define rotating blocks near the intersection of the San Andreas and San Jacinto faults (left side inset A, Figure 1). During a large earthquake, right-slip motion (*i*) occurs on one of the major bounding faults; however, during the interseismic period, the major faults 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* and *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 subparallel left-lateral faults previously identified by *Hadley and Combs* [1974].

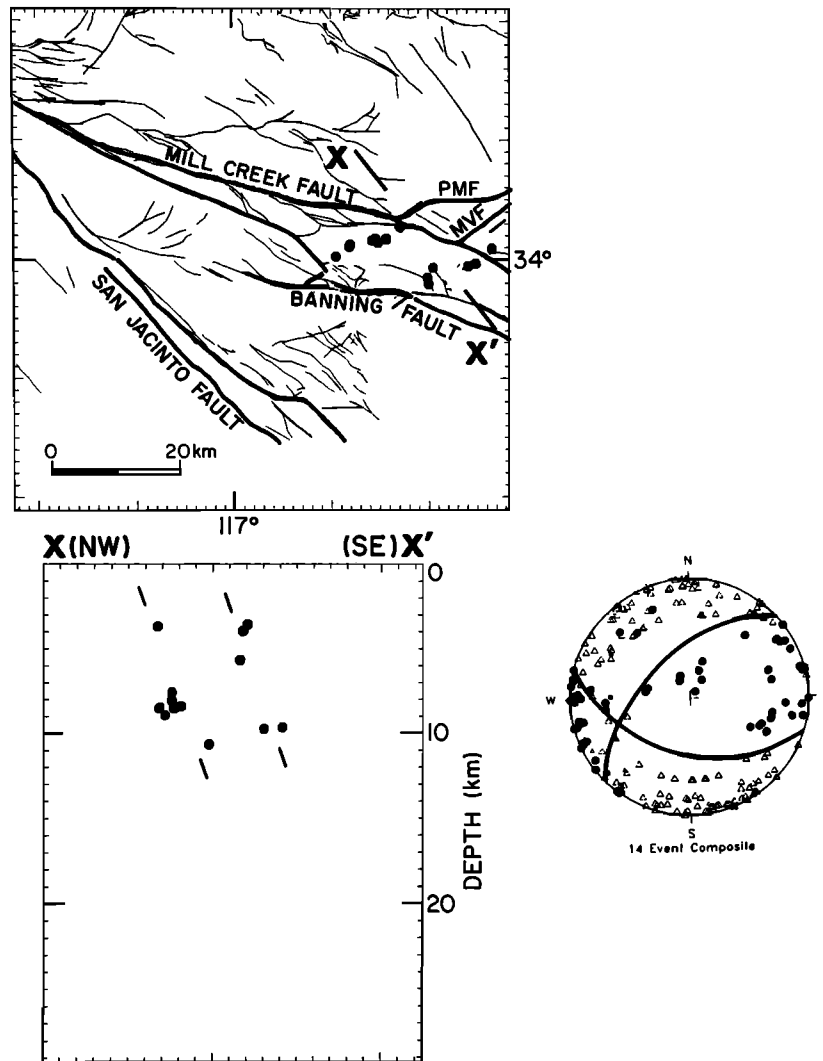


Fig. 3. Map and cross section of a select group of earthquakes, between the Mill Creek and Banning faults (right side inset *A*, Figure 1), that exhibit the particular composite focal mechanism shown at right. These earthquakes align along planes that dip steeply to the south and reflect compressional left slip along northeast-oriented nodal planes.

tion is inferred to have taken place on low-angle detachments and high-angle thrust faults similar to the pattern observed in the seismicity, and would imply that the San Bernardino Mountains are allochthonous. Regional gravity data and the distribution of P_g velocities also tend to support this interpretation [Hearn and Clayton, 1984].

ADDITIONAL EVIDENCE FOR LEFT-LATERAL FAULTING AND BLOCK ROTATION

Seismology

Other areas in southern California that currently exhibit left slip on what appear to be conjugate fault structures include much of the region east of the southern San

Andreas and south of the Pinto Mountain fault (inset *B*, Figure 1). Relocated earthquake hypocenters define en echelon sets of planar zones that strike northeast to east-west and align in both map and cross section [Williams *et al.*, 1984]. These earthquake alignments match other fault orientations identified on the basis of extensive field mapping [Powell, 1981] or inferred from gravity studies [Biehler *et al.*, 1964]. Focal mechanism solutions of earthquakes close to the San Andreas fault are consistent with left slip on nearly vertical northeast-striking faults (Figure 5) that appear to separate the aftershocks of the 1947 Morongo Valley earthquake ($M_L=5.5$) from those of the 1948 Desert Hot Springs event ($M_L=6.5$) [Richter *et al.*, 1958].

Figure 6 shows another set of earthquake epicenters

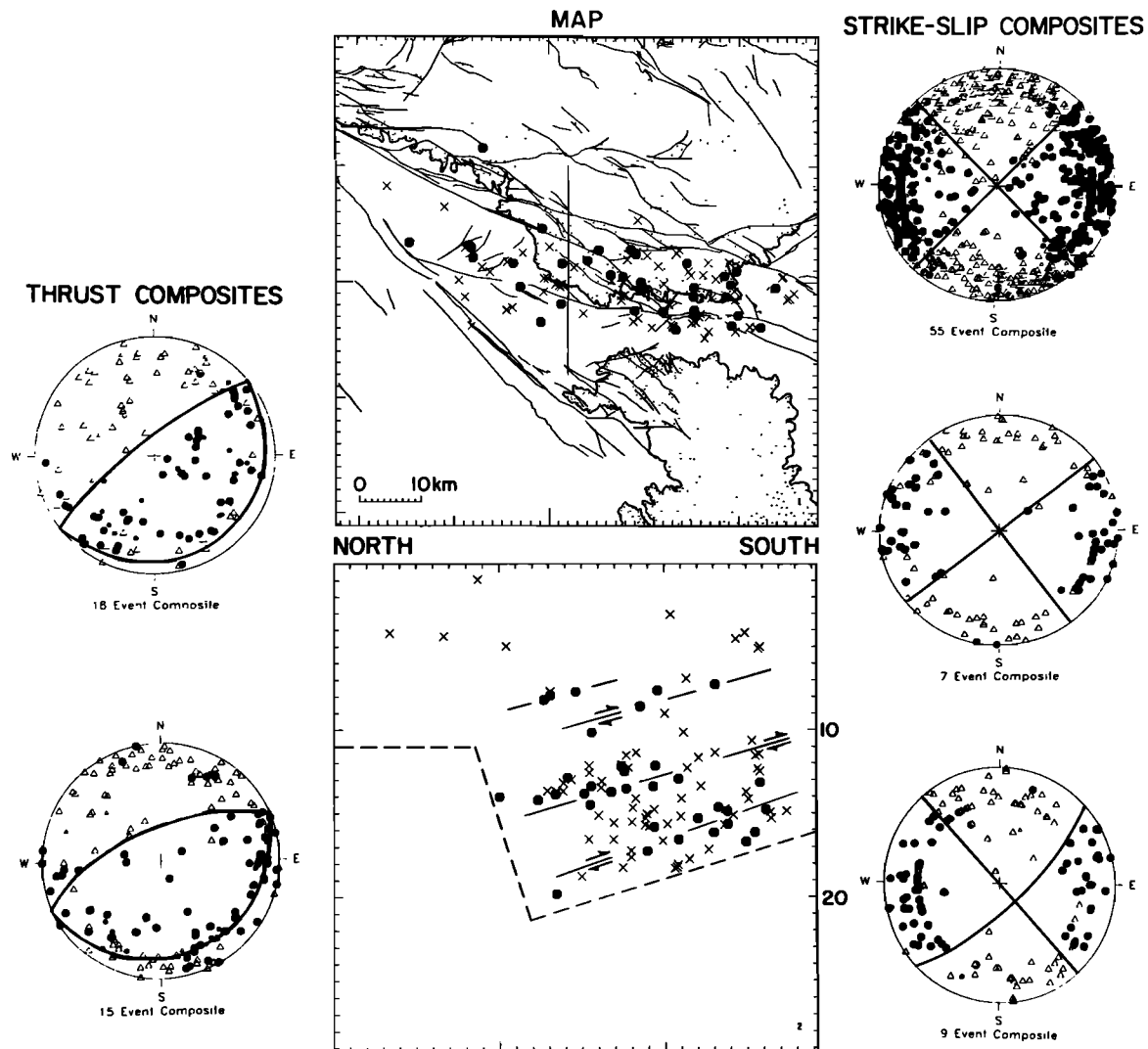


Fig. 4. Map and cross section of the predominantly deeper strike-slip (X's) and low-angle thrust events (solid circles) near San Gorgonio Pass (inset A, Figure 1). The thrust earthquakes define a series of planes that dip to the north and parallel the gently dipping interface that defines the base of the seismogenic zone (dashed line) and match the low-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 Mountains to the north and the San Jacinto Mountains to the south. Shaded areas represent elevations above 3,000 feet (≈ 1 km).

that define two northeast linear features parallel to the southern end of the Salton Sea, connecting the Brawley seismic zone with the Superstition Hills fault (inset C, Figure 1). Motion along the northeast trends is predominantly left-lateral, and in many ways mirrors the fault structure seen in Figure 2. Block boundaries defined by these faults appear to be major controlling influences on the distribution of both seismic and aseismic slip in the region, as well as on local hydrology.

For instance, triggered slip along the Superstition Hills fault following the 1968 Borrego Mountain earthquake ($M_L=6.8$) and the 1979 Imperial Valley earthquake

($M_L=6.6$, $M_w=6.5$) was localized to a section defined by the two northeast-striking subsurface faults [Fuis, 1982]. The largest aftershock of the 1979 earthquake ($M_L=5.8$) occurred near Brawley within 8 hours of the mainshock, on what was apparently the southernmost of the two northeast faults (see focal mechanism Figure 6) [Johnson and Hutton, 1982]. Slip propagated from southwest to northeast, and the event was strongly felt in Brawley. A similar situation may also have occurred shortly after the 1940 Imperial Valley earthquake ($M_L=6.5$, $M_w=7.1$). The largest aftershock occurred within 80 minutes and caused more damage in Brawley than the mainshock

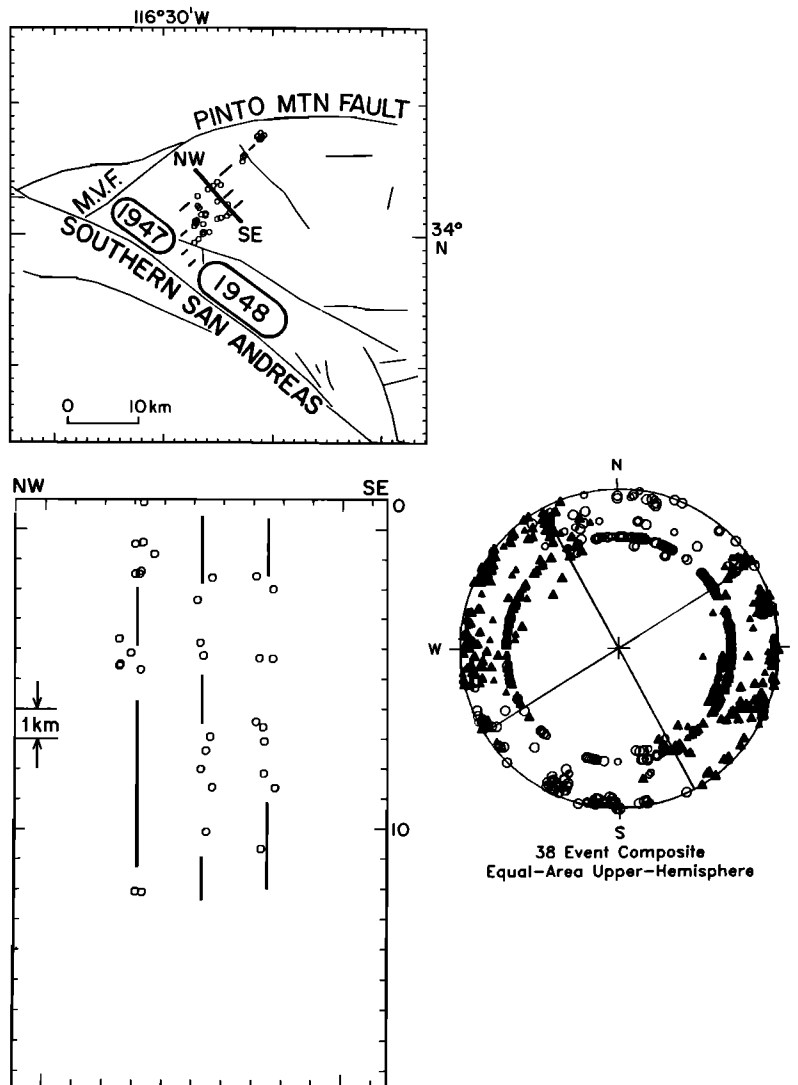


Fig. 5. Map, cross section and composite focal mechanism of strike-slip earthquakes close to the southern San Andreas and south of the Pinto Mountain faults (inset B, Figure 1). Earthquake hypocenters define a series of nearly vertical planar structures that strike northeasterly, and appear to separate the aftershocks of the 1947 Morongo Valley earthquake from those of the 1948 Desert Hot Springs event [Richter *et al.*, 1958]. Motion along these northeast planes would be left-lateral [after Williams *et al.*, 1984].

[Richter, 1958]. Based on the identification of an active conjugate fault near Brawley, and the similarity between the two large aftershocks, left slip during the large 1940 aftershock can not be precluded [Johnson and Hutton, 1982].

Two years later, in 1942, a large earthquake on the Superstition Hills fault ($M_L=6.5$) was followed 10 hours later by a large aftershock ($M_L=5.5$) on the Brawley seismic zone (Figure 6). Given the uncertainty in earthquake locations, however, the exact position of these two events is not known; but it is interesting to note that, 2 years after the 1979 earthquake (like the 1940 event), a

large ($M_L=5.7$) earthquake occurred on the Brawley seismic zone near the town of Westmoreland. It was part of a large swarm of earthquakes totaling more than 2,000 locatable events and nearly all were located along the northernmost of the two northeast features shown in Figure 6 [Hutton and Johnson, 1981]. Rupture apparently initiated close to the intersection with the north-northwesterly trend of the Brawley seismic zone, and propagated to the southwest, consistent with the left-lateral nodal plane seen in the mainshock focal mechanism.

Confirmation of northeast-striking structures is also evident in the local hydrology. Hydrothermal springs and the

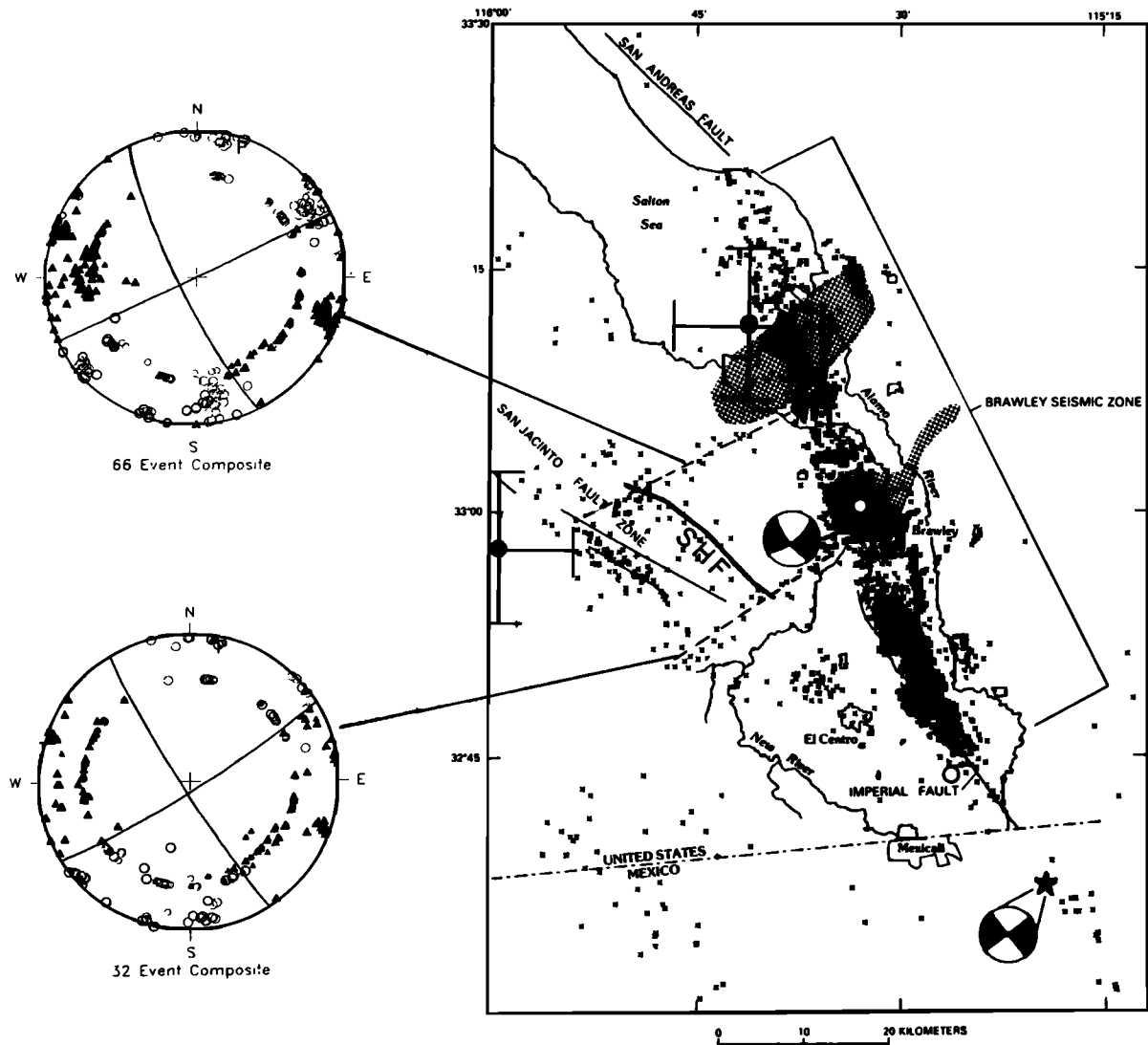


Fig. 6. Earthquake epicenters from 1973 to 1978 [after Johnson and Hill, 1982]. Composite focal mechanisms are for earthquakes between the Superstition Hills fault (SHF) and the Brawley seismic zone south of the Salton Sea (inset C, Figure 1). These events define a set of two nearly vertical planar features that match the left-lateral northeast-striking nodal plane seen in the composite fault plane solutions. These planar features parallel the southern end of the Salton Sea and may have controlled the distribution of triggered slip (heavy line) along the Superstition Hills fault following the 1979 Imperial Valley earthquake (star) Other events that appear temporally related are: 1940 Imperial Valley earthquake and its large aftershock near Brawley (open circles); 1979 earthquake and its large aftershock near Brawley (focal mechanisms); 1942 earthquake and its large aftershock near the Salton Sea (closed circles with error bars). Shaded areas represent regions of high heat flow and anomalous travel-time residuals.

pattern of high heat flow (shaded area, Figure 6) define an elongate northeast trend, parallel to the southern end of the Salton Sea [Jennings et al., 1975; Fuis et al., 1982]; and the course of the New River takes a dramatic sidestep that strikes northeasterly, parallel to the extrapolated surface trace of the northeast seismicity trend just north of the town of Brawley (Figure 6).

On a somewhat smaller scale, analysis of the broad band of earthquakes that makes up the Brawley seismic zone suggests that, north of the surface rupture involved in the 1979 earthquake, the Brawley zone is not a single simple fault. Instead, a complicated series of en echelon northeast-striking left-lateral faults intersect others that trend north or northwest [Johnson and Hadley, 1976;

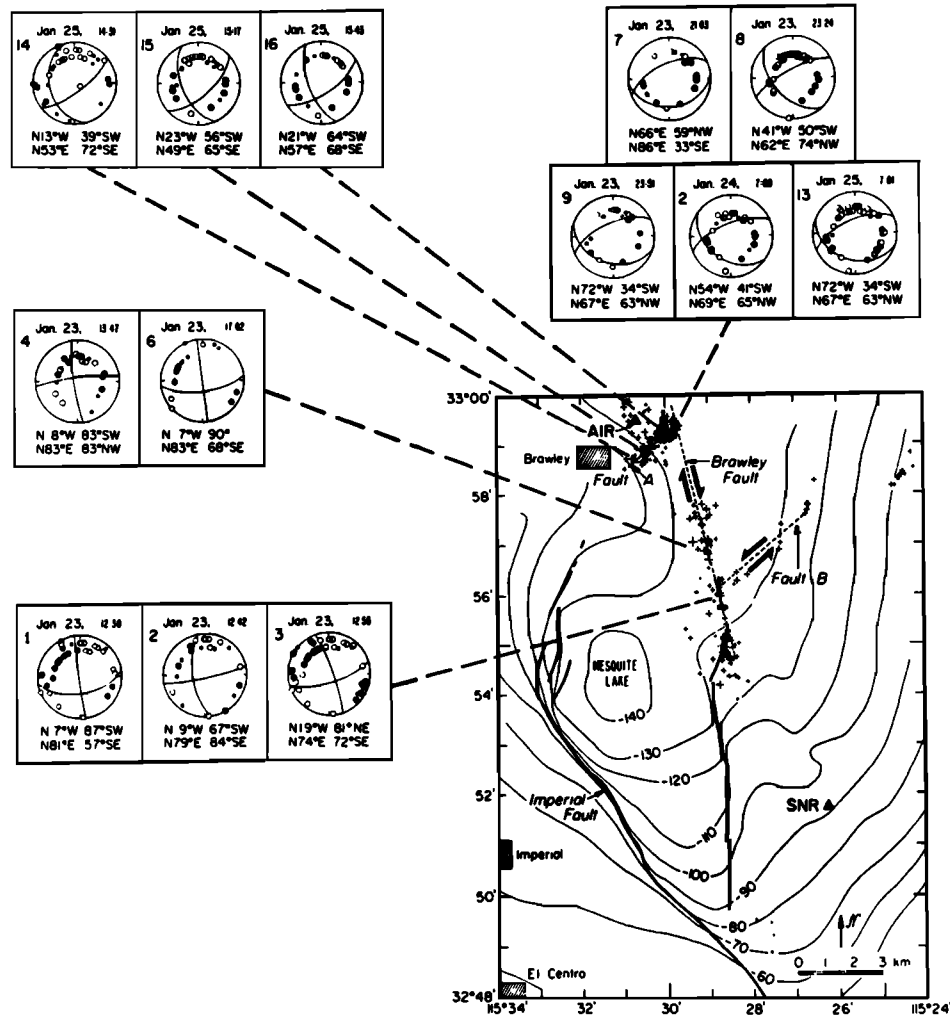


Fig. 7. Earthquake epicenters and single-event focal mechanisms for a set of events that occurred during the 1975 Brawley swarm [after Johnson and Hadley, 1976].

Johnson and Hill, 1982; Fuis et al., 1982]. These short fault segments appear to define sets of small crustal blocks and are best delineated by intense swarms of small earthquakes that often characterize activity in the Brawley region [Johnson, 1977; Hill, 1977]. Figure 7 shows a set of locations from an earthquake swarm in 1975 [Johnson and Hadley, 1976]. Epicenters define two northeast-striking left-lateral faults connected by the right-lateral north-northwest-striking Brawley fault. Focal mechanisms of earthquakes along the seismicity trend just south of Brawley (fault A), however, exhibit an unusual pattern in both space and time. At the corner where fault A intersects the Brawley fault, a series of reverse faulting earthquakes occurred from January 23 to 25. Activity then migrated towards the southwest, with the pattern of faulting changing from reverse to one of increasing normal slip, in addition to the presence of a large component of left-lateral motion.

Models invoked to explain the deformation observed along the Brawley seismic zone usually involve pull-apart basins or small-scale spreading centers at right-steps in major right-lateral transform faults [e.g., Lomnitz et al., 1970; Fuis et al., 1982]. Weaver and Hill [1979] propose a model for continental pull-apart basins that involves oblique spreading and distributed dextral and sinistral slip. These models fail to explain, however, the presence of reverse faulting within the Brawley extensional environment, or account for the large amounts of left slip along what many of the models would predict as primarily normal faults. Alternatively, this pattern of deformation is exactly what would be predicted by a block rotation model. And in fact, block rotation by strike-slip faulting is facilitated if shear is distributed between fault zones or fault systems of finite width where extension occurs parallel to the major strike-slip faults [Cox, 1980].

Another aspect of southern California seismicity that a

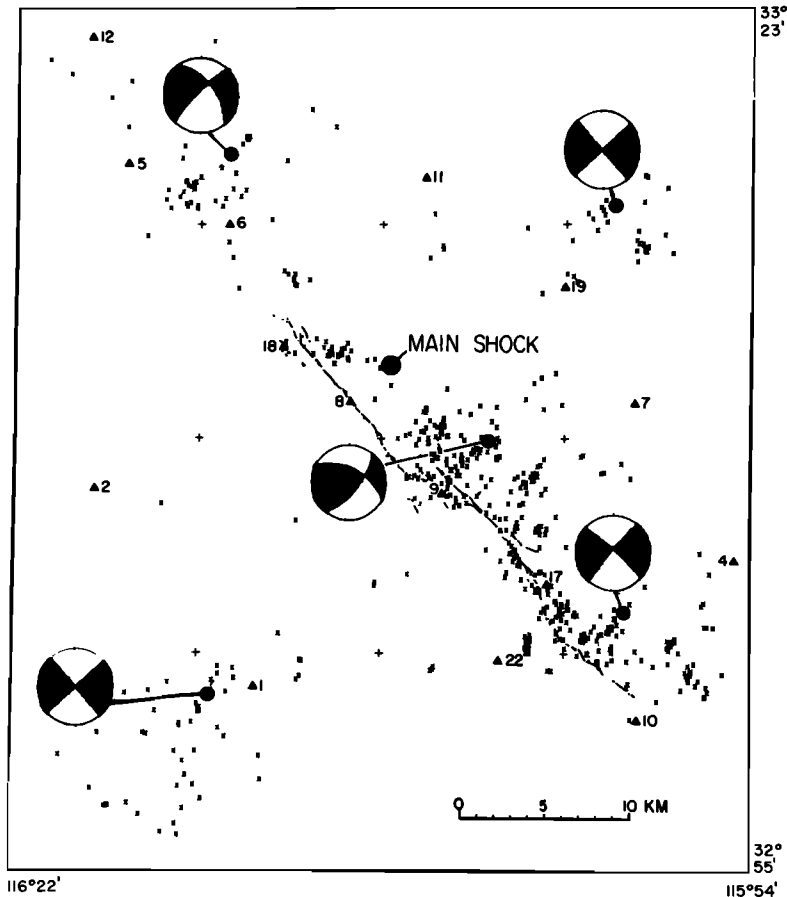


Fig. 8. Aftershocks (crosses), ground breakage, and main shock of the 1968 Borrego Mountain earthquake ($M_L=6.8$) that occurred on the Coyote Creek fault (inset D, Figure 1) [after Hamilton, 1972]. Focal mechanisms are lower hemisphere projections (compression quadrants shaded) of representative single events.

block rotation model, or at least the presence of active conjugate faults, may explain is aftershock zones of major strike-slip earthquakes that do not define single simple vertical faults. Figure 8 shows the seismicity following the 1968 Borrego Mountain earthquake (inset D, Figure 1). Both foreshocks and aftershocks were found to occur in two clusters well off the main fault trace [Hamilton, 1972; Sanders and Kanamori, 1984]. Das and Scholz [1981] explain the presence of the 'off-fault' aftershock activity as slip along preexisting structures induced by increased shear stress caused by the mainshock. Whether these events represent slip on left- or right-lateral surface faults and northeast-oriented structures in basement topography have been identified in these areas from regional mapping [Engel and Schultejan, 1984] and travel-time anomalies [Fuis et al., 1982]. Aftershock locations also extend up to 10 km away from the main surface fault trace, and in many cases, define short linear trends with northeast orientations. Focal mechanism solutions of these events are consistent with left slip on second-

dary transverse structures; whereas, the right-lateral nodal plane is sometimes rotated from the general strike of the main fault trace.

Geology

Detailed mapping of existing geologic structures in southern California and northern Mexico (Baja California) reveals a number of low-angle thrust surfaces and left-slip faults much like those suggested by the seismicity [Crowell, 1975; Yeats, 1981; Powell, 1981; Engel and Schultejan, 1984; Angelier et al., 1981; Frost and Okaya, 1985]. Other studies based on well data, seismic refraction data and reduced travel-time anomalies imply similar northeast-striking orthogonal structures in the basement topography surrounding the Imperial Valley region [Fuis et al., 1982]. Several of these secondary subsurface features are located between the Elsinore and San Jacinto faults, and are likely responsible at least in part for the large amount of seismic activity that exists between the two fault zones (Figure 1). Many of these

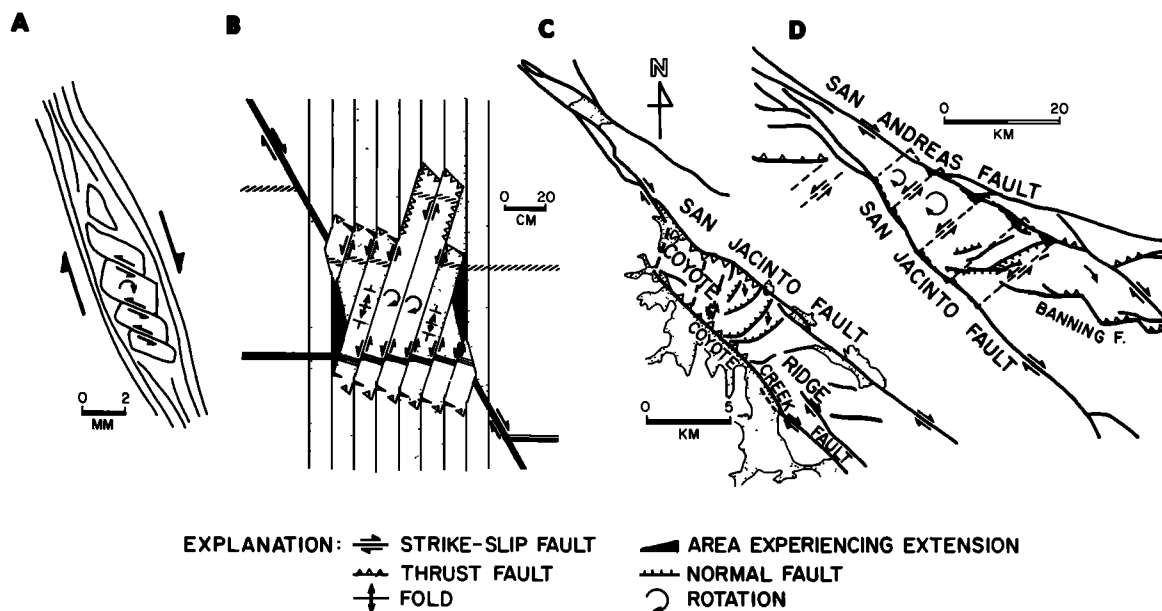


Fig. 9. Geologic examples of block rotation by strike-slip faulting on scales from millimeters to kilometers. (a) Fracture and rotation of a feldspar crystal along cleavage planes in a ductile matrix [Simpson and Schmid, 1983]; (b) rotation of a hard desiccated surface layer caused by the mole track of the 1979 Imperial Valley earthquake and controlled by evenly-spaced furrows of a plowed field (ruled lines) [Terres and Sylvester, 1981]; (c) rotating blocks defined by secondary cross faults between an overlapping right-step from the Coyote Creek fault to the San Jacinto fault (inset E, Figure 1) [Seeber and Nicholson, 1986]; (d) block model for shear rotation near the intersection of the San Jacinto and San Andreas faults inferred from geology and seismicity (Figure 2) [Matti et al., 1985; Nicholson et al., 1986].

nearly orthogonal structures predate the modern San Andreas system and may provide the necessary slip surfaces to facilitate shear rotation during strike-slip deformation. If these older structures are effectively segmenting southern California into discrete crustal blocks, efforts must be made to determine the extent to which these blocks are involved in the overall pattern of seismic deformation and strain accumulation.

Block behavior (i.e., the amount and sense of rotation) is strongly coupled to the size and strength of the blocks involved, and whether slip along faults defining rotated domains is accomplished on major or minor faults [Ron et al., 1984]. Figure 9 documents geologic evidence for block rotation on scales from millimeters to tens of kilometers. Blocks of even larger dimensions have been suggested to account for the counterclockwise rotation of the Mojave region [Garfunkel, 1974], the overall deformation of southern California [Luyendyk et al., 1980], and for the presence of large-scale tectonic structures observed between the broad zones of shear affecting the northern and southern boundaries of the Caribbean plate [Skerlec and Hargraves, 1980]. On a scale of meters to kilometers, Young et al. [1985] describe the development of Tertiary rotational features and the evolution of an extensive rotating block system along transform faults in Iceland.

Factors that appear to control the dimensions of blocks are largely the spacing between secondary faults and the depth to either a detachment or ductile shear zone. Thus,

in the case of Figure 9a, blocks are defined by crystal cleavage planes [Simpson and Schmid, 1983]; whereas in Figure 9b, deformation of the hard "caliche-like" surface sediment caused by the mole track of the 1979 Imperial Valley earthquake was controlled by preexisting evenly spaced furrows of a plowed field and the depth to a more ductile moist sublayer [Terres and Sylvester, 1981].

Where preexisting zones of weakness are not present, antithetic slip may be accommodated by new faults that form, similar to the conjugate faults observed in laboratory experiments [Wilcox et al., 1973]. Figure 9c shows the deformation associated with the right-step between the San Jacinto and Coyote Creek faults (inset E, Figure 1). Within the zone of overlap between the two faults are several secondary faults with a dip-slip component and orientations appropriate for a pull-apart basin [Rodgers, 1980]. However, instead of a basin, a prominent topographic high (Coyote Ridge) is present topped by young alluvial sediments [Sharp, 1967]. Seeber and Nicholson [1986] explain the rapid uplift and presence of the outward directed thrust faults (Figure 9c) along the San Jacinto and Coyote Creek faults as the result of block rotation. In their model, new blocks form at the northwestern end as new faults develop close to the direction of maximum compressive stress. These blocks then rotate clockwise by left slip along the newly formed cross faults in response to right-lateral shear, increasing their projected length perpendicular to the overall fault zone. This

increased dimension causes localized compression, the observed uplift, and a decrease in the amount of right slip experienced by the major bounding faults. As blocks continue to rotate beyond perpendicularity, compression across the fault zone is relaxed, extension parallel to the fault zone is enhanced, rotation diminishes, and right slip resumes, primarily on the Coyote Creek fault. Thus, in addition to providing a means for accommodating slip across a major en echelon fault offset, a block rotation model can account for a number of features characteristic of the deformation observed along Coyote Ridge, including: the timing, orientation and sense of slip of the cross faults; variable slip rates along the major right-lateral faults; and the observed uplift in an area otherwise expected to experience extension and subsidence.

A seismic analog to the deformation observed along Coyote Ridge is exhibited by the aftershocks of the 1979 Coyote Lake earthquake that occurred on the Calaveras fault in central California. Hypocenters of a number of aftershocks define a set of nearly orthogonal northeast-striking cross faults between a zone of en echelon offset between the two northwest-striking rupture planes responsible for slip in the main shock [Reasonberg and Ellsworth, 1982]. Slip along these secondary faults as determined from focal mechanism solutions is left-lateral and is consistent with a set of small crustal blocks rotating clockwise as a result of distributed shear within the zone of overlap [Seeber and Nicholson, 1986]. In this case, block geometry appears to have been governed by a preexisting regional fault pattern.

Similarly, the kinematic model proposed to explain the seismicity pattern illustrated in Figure 2 (Figure 9d), accounts for the presence of northeast-striking left-lateral subsurface faults that terminate against major wrench fault boundaries. Further confirmation that such transverse structures are active and may be accommodating shear-induced rotation is suggested by minor deflections in the strikes of both the San Jacinto and San Andreas faults; and by the presence of alternating transensional and transpressional features observed along strike of the San Andreas fault where rotating block corners would affect the pattern of wrench fault deformation (Figure 9d) [Matti et al., 1985]. Larger deflections in fault strike, which could be caused by or related to block rotation, are found farther south along the southern San Andreas, and correlate with the locations of triggered slip after major southern California earthquakes, and the positions of localized compressive features, such as the Indio Hills, the Mecca Hills and Durmid anticline [Bilham and Williams, 1985]. Clockwise rotation of material can also account for the increased uplift observed from west to east along the presently active northward-dipping thrust faults that form the Banning fault zone through San Geronio Pass (Figure 9d) [Matti et al., 1985].

Experimental Models and Related Topics

Block rotation by strike-slip faulting is responsible for a number of structural relationships and small-scale tectonic features observed along major wrench faults [Ron et al.,

1984; Garfunkel and Ron, 1985; Christie-Blick and Biddle, 1985]. The presence of rotating blocks has long been argued on purely structural grounds [Dibblee, 1954, 1977; Cloos, 1955; Carey, 1958; Freund, 1970, 1974; Beck, 1976, 1980; Cox, 1980; Walcott et al., 1981; Ron et al., 1984]. Laboratory experiments confirm that antithetic structures like those identified between the Coyote Creek and San Jacinto faults often form during strike-slip deformation through homogeneous materials [e.g., Tchalenko, 1970; Wilcox et al., 1973]. These secondary faults, termed conjugate Reidel shears, are found to rotate above basal master faults as slip continues and deformation increases [e.g., Hempton and Neher, 1985]. Conditions favoring block rotation over translation by simple shear are (1) the overall width of the deformational zone between which shear is distributed; (2) the strength of the deforming material relative to the zone of low shear resistance at depth; (3) the orientation of the regional stress field; and (4) the initial angle at which secondary faults form or preexisting faults are situated relative to the major strike-slip faults that define the zone of shear [Seeber and Nicholson, 1986]. Domains bounded by right-lateral faults will tend to form fairly evenly spaced left-lateral cross faults and rotate clockwise; domains bounded by left-lateral faults will tend to form right-lateral secondary faults and rotate counterclockwise. Simple geometry then relates block dimensions and the amount of rotation to the overall slip accommodated by either the master bounding faults or the secondary cross faults [e.g., Freund, 1974].

Paleomagnetism

The seismic data examined so far require neither large rotations nor large left-lateral displacements, but if rotations persist and accumulate with time, then large deflections from the magnetic pole at the time of deposition would be expected in rocks of sufficient age involved in the wrench fault tectonics of the San Andreas system. Luyendyk et al. [1985] and Christie-Blick and Biddle [1985] summarize much of the available paleomagnetic data for southern California. They show that for large parts of the region, large clockwise deflections are observed in deposits of Neogene and Quaternary age (Figure 10). Other studies have found similar results farther north along the plate boundary, and all correlate with the long-term regional right-lateral shear affecting the western edge of North America [e.g., Beck, 1980].

Kinematically, these measurements correlate with the dominant regional fault pattern and match observations elsewhere in areas affected by wrench fault tectonics [Freund, 1970, 1971; Walcott et al., 1981; Ron et al., 1984; Skerlec and Hargraves, 1980; Young et al., 1985]. Previous models used to explain these observations typically invoke large rotations of large (i.e., > 50 km) rigid blocks [e.g., Luyendyk et al., 1980]. If however these measurements are the result of shear rotation involving only small crustal blocks, wedges or slices, then both the paleomagnetic data are satisfied and many of the geologic contradictions related to the rotation of large rigid blocks are avoided [Wells and Coe, 1985]. Geologic evidence for distributed shear involving small blocks rather than the

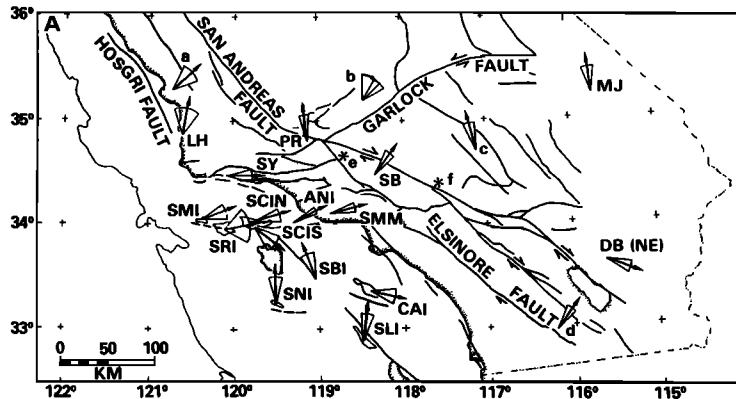


Fig. 10. Paleomagnetic declinations measured in rocks of Neogene and Quaternary age (see *Christie-Blick and Biddle* [1985] for a complete review). The mean declination and 95% confidence limits are shown for each site. Most sites west of the San Andreas and south of the Pinto Mountain fault exhibit clockwise tectonic rotations consistent with distributed right-lateral shear.

rigid rotation of large blocks is documented by abundant reactivated mylonitic zones with left-lateral displacements observed throughout the San Gabriel block [May, 1985], a prominent fault-bounded terrane adjacent to the San Andreas that experienced large clockwise rotations in the Miocene (point *SB*, Soledad Basin, Figure 10) [Terres and Luyendyk, 1985].

Paleomagnetic data also provide constraints on the timing, evolution, and speed at which shear rotations can occur. These data show that in some cases, tectonic rotations are quite rapid, particularly in areas where blocks are small. *Johnson et al.* [1983] describe the Quaternary deformation of the Vallecito-Fish Creek basin adjacent to the Elsinore fault (point *d*, Figure 10). This basin underwent 35° of clockwise rotation in less than 0.9 Ma after sedimentation ceased, and the basin uplifted in a manner that may have been similar to the proposed history of Coyote Ridge. Numerous faults are evident within the basin, and given the average dimensions of the blocks involved, this rate of rotation corresponds to an average slip rate along the Elsinore of about 5–7 mm/yr. Although this rate of fault slip is higher than some earlier estimates [e.g., *Bird and Rosenstock*, 1984], it is within the range of recent Quaternary slip measurements based on trenching [Rockwell *et al.*, 1985].

In another example, poorly consolidated sediments adjacent to the San Jacinto fault, just south of Coyote Ridge, exhibit 20° to 30° of clockwise rotation in the last 0.7 to 1.0 Ma [Seeber and Bogen, 1985], corresponding to an average rate of rotation of 0.3–0.6 $\mu\text{rad/yr}$. These data imply that periods of shear rotation, like displacements, can be episodic, but once conditions are favorable, rotations do occur and are closely coupled to the wrench fault tectonics of the San Andreas system.

Geodesy

Rapid rates of rotation have also been observed in geodetic data. In central California, *Prescott et al.* [1981] document a rotational rate of 0.3 $\mu\text{rad/yr}$, which if sus-

tained corresponds to 17°/Ma for a small block bounded on the west and north by the Calaveras and Los Positas faults. Triangulation surveys along the Alpine fault in New Zealand also exhibit relatively high rates of tectonic rotation, on the order of 8°/Ma [Walcott, 1984]. In the case of the Alpine fault, the short-term geodetic values are consistent with longer-term rates measured paleomagnetically. These show a gradual increase in the amount of plate boundary deformation taken up by shear rotation since the orientation of the plate motion vector became more oblique to the Alpine fault system about 5 Ma ago [Walcott, 1984]. This suggests that a certain degree of coupling perpendicular to the fault zone is required before rotations are observed. Places where the plate motion vector is nearly parallel to the major plate boundary (i.e., the creeping section of the San Andreas fault in central California) would not be expected to exhibit large amounts of shear rotation. Nevertheless, the correlation between short-term geodetic measurements and long-term cumulative effects determined geologically or paleomagnetically bears directly on the process of how strain is partitioned between both elastic and nonelastic deformation, as well as the extent to which tectonic rotations accommodate shear within wrench fault environments.

DISCUSSION

If these results have applications elsewhere along the San Andreas system, they provide several new concepts for understanding the kinematic behavior and fault tectonics for southern California. Low-angle structures like detachments may be involved in contemporary strike-slip deformation and, in the analysis of regional strain data, rotations must be considered. Classical interpretations of small-scale tectonic features along major wrench faults that assume irrotational models [e.g., *Crowell*, 1974; *Rodgers*, 1980; *Seagall and Pollard*, 1980; *Aydin and Page*, 1984] may need to be modified to allow for various degrees of block rotation, particularly between fault zones or fault systems of finite width. Thus, in areas where

shear is distributed, deformation is likely to be inhomogeneous and largely controlled by block geometry and the kinematics of block interaction [Bilham and Beavan, 1979; Garfunkel and Ron, 1985]. Both the elastic and nonelastic behavior of the crust will strongly depend on the nature of any preexisting fabric and the depth to either a decollement or ductile shear zone. More important, the pattern of deformation observed during the interseismic period may differ significantly from the type of deformation expected to take place during a large earthquake. Thus, in southern California, current seismicity may not be simply related to the tectonic effects associated with major earthquakes on through-going branches of the San Andreas fault. This is because large earthquakes are generally the result of right-lateral slip along major faults (*I*, Figure 2); whereas much of the present activity is on secondary faults, some of which are accommodating left-lateral motion as a result of block rotation (*E, F, G, H, J*, Figure 2).

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 the San Jacinto fault (Figure 1), and for the location of small-scale transpressive features observed along the southern San Andreas [Sylvester and Smith, 1976]. Furthermore, as block rotation appears most prevalent in areas where major faults splay, overlap or converge, regions of high earthquake activity along the San Jacinto may thus reflect areas of abundant secondary cross faults within fault-bounded domains.

Block rotation will also change the initial angle between existing left- and right-lateral faults, as well as their orientation relative to the regional stress field [Garfunkel and Ron, 1985; Seeber and Nicholson, 1986]. This explains how minor inflections in the strikes of major wrench faults continue to develop, why secondary faults may change their sense of slip with time, why rotations eventually cease or reverse, and why new faults may form as old faults are rotated into positions unfavorable for further slip. Because faults and fault slip are thus responding to local kinematic constraints, once finite rotations have occurred, directions of regional stress will no longer be simply related to existing fault orientations. Anomalous focal mechanisms, that in some cases have led to inferences of time-dependent rotation of principal stress axes [e.g., McNally et al., 1978], are more likely the result of a rotating fault geometry, or possibly antithetic slip on a conjugate cross fault, rather than any actual change in the regional stress field. However, as the strikes of faults cannot rotate across principal stress axes [Garfunkel and Ron, 1985], rotations much larger than about 60° can only occur if new faults form, or the orientation of the stress field does indeed change [Ron and Nur, 1985].

An important aspect of a block rotation model is that block dimensions and the orientation of secondary cross faults may control the characteristic size of earthquake ruptures. Examples are the orthogonal left-lateral faults that appear to have controlled the distribution of slip in

the 1948 and 1947 earthquakes (Figure 5); and the ruptures in both the 1940 and 1979 Imperial Valley earthquakes (Figure 6) that repeatedly stopped short of crossing the northeast seismic lineation near Brawley.

Nucleation sites and the rupture behavior of large earthquakes may also be influenced by proximity to changes in the geometry of block boundaries and the location of where major faults intersect [e.g., Lindh and Boore, 1981; Jones, 1984]. This effect may be responsible for observed cross-patterns in foreshocks or aftershocks, as in the case of the Borrego Mountain earthquake of 1968 [Sanders and Kanamori, 1984], the Homestead Valley sequence of 1979 [Hutton et al., 1980], or the Manix earthquake of 1947 [Richter, 1958]. Even moderate size earthquakes on left-lateral cross faults generally initiate near major fault intersections, as demonstrated by the rupture behavior of the large Brawley aftershocks (1940, 1979), the Westmoreland earthquake (1981), and the recent San Bernardino Valley earthquake (1985). King and Nábělek [1985] describe a number of cases where rupture behavior and the nucleation point of large earthquakes is controlled by fault geometry and in particular, by the location of major fault offsets or bends. If such bends are renewed or created by block rotation, this suggests that off-fault activity on secondary cross faults and the kinematics of block rotation may have a much stronger influence (and therefore predictive value) on the behavior of major wrench faults than previously had been supposed.

Block corners can rotate into the major bounding faults, indenting the slip surface, and thereby create time-dependent asperities that impede fault movement [Seeber and Nicholson, 1986]. Thus, in areas where current seismic activity is related to block rotations (rotations that may not be particularly conducive to right-lateral slip along major wrench faults), a change in the pattern of seismic deformation may be required preparatory to failure in a great earthquake. How and in what form this precursory activity may take is uncertain. In the eight years prior to the 1948 Desert Hot Springs event, an unusual number of $M_L \geq 5$ earthquakes occurred within a 50 km radius of the eventual epicenter [Sykes and Seeber, 1985]. The 1968 Borrego Mountain earthquake was also preceded by a number of small shocks on either side of the main fault that may be interpreted as representing activity on secondary cross faults. In a more recent case, the 1970 Lytle Creek earthquake ($M_L=5.4$), located north of Cajon Pass on a subsidiary branch of the San Jacinto fault, was preceded by a small foreshock just off the main fault trace [Jones, 1984], and it too may have reflected slip on a possible cross fault. Unfortunately, less than half of all major strike-slip earthquakes in California are preceded by foreshock activity [Jones, 1984].

Blocks defined by secondary transverse structures can also act as interlocking cogs to effectively transmit strain changes over greater distances than predicted by simple dislocation theories. The occurrence of large aftershocks at considerable distances following the 1940 and 1979 Imperial Valley earthquakes, and the large aftershock on the Brawley fault following the 1942 Superstition Hills earthquake (Figure 6) are notable examples.

Of course, not all left-slip motion on secondary cross

faults signifies block rotation. Such displacements may simply be the response of preexisting fault structures to the present regional stress field that currently has a maximum horizontal compressive stress axis that strikes just east of north [e.g., *Zoback and Zoback, 1980*]. The presence of orthogonal structures, however, does imply that the upper crust is more likely to exhibit block tectonic behavior [e.g., *Hill, 1982*], and is more likely to experience finite rotations once shear becomes distributed.

How much strain is actually accounted for by shear rotation is uncertain. The partition between simple translation and block rotation may vary considerably in both space and time. The evidence from paleomagnetism and the analysis of structural elements along major wrench faults suggests that at least a component of the long-term geologic deformation is accomplished by block rotations. On the other hand, evidence from geodesy and seismicity indicates that shear rotations are also accommodating current accumulations of regional shear during the interseismic period. This similarity in short and long term kinematics implies that not all interseismic deformation reflects stored elastic strain energy that is eventually released as slip during large or great earthquakes [e.g., *Reid, 1910*]; but rather some strains are permanent and eventually accumulate to produce the large tectonic rotations observed. Whether the converse is also true has yet to be determined. That is to say, some rotations (particularly on a small-scale) may be involved in the dynamics of earthquake ruptures and can thus be recovered during slip in large earthquakes. The observation that aftershocks of some moderate right-slip earthquakes exhibit focal mechanism solutions that are rotated counterclockwise 5° to 10° relative to the orientation of foreshock focal mechanisms [*Lindh et al., 1978*], may be indicative of such recovered finite rotations during the mainshock.

In terms of conjugate faulting, although the total amount of seismic energy released by left slip on secondary faults is small compared to the amount of right slip observed in large earthquakes, the actual numbers of left-lateral earthquakes involved in the contemporary seismic deformation of southern California appears to be quite large. In particular, whenever dense clusters of seismic activity have been closely examined, they have generally been found to exhibit closely-spaced northeast-striking left-lateral faults. A good example is of course the Brawley seismic zone. Thus, although right-lateral earthquakes in southern California are clearly responsible for most of the displacement and nearly all the seismic energy released along the plate boundary, excluding areas where the morphology of right-lateral faults is fairly simple (e.g., the Imperial fault), few earthquakes at present define well-developed northwest lineations with focal mechanisms that show a consistent northwest-oriented nodal plane that parallels the local strike of the major through-going fault.

CONCLUSIONS

Microearthquakes in southern California presently exhibit an unusual pattern of seismic deformation. Few earthquakes can be directly related to right-lateral slip

along major fault structures. Instead, earthquakes tend to cluster in areas where major faults splay, or define short linear segments that sometimes strike northeasterly and are nearly orthogonal to the regional pattern of fault orientation (Figure 1). Motion along these secondary transverse structures is predominantly left-lateral and is consistent with a set of small crustal blocks rotating as a result of regional right-lateral shear.

A block rotation model accounts for a number of small-scale tectonic features observed along major wrench faults in California, and matches other data, both long-term (geologic and paleomagnetic) and short-term (geodetic), that suggest shear rotations are a persistent feature of the San Andreas system. Rotations produced by tectonic shear, however, are likely to be nonuniform in both space and time, and are likely to be concentrated in areas where shear is distributed between fault zones or fault systems of finite width, in the vicinity of major fault bends, or in areas experiencing fault-parallel extension. As rotations about a vertical axis require a decoupling surface at depth, this implies that detachments of either local or regional extent are involved in the contemporary wrench fault deformation of southern California.

How long this particular pattern of kinematic behavior will persist 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 high probability of identifying the precursory change and thereby predicting the impending large earthquake and the occurrence of large right-lateral displacements. Even if this should fail to happen, a rotating block model would still be useful in terms of identifying the local kinematic constraints of fault interaction and the places where bends, offsets, and other major deflections in the geometry of subsurface faults are likely to occur. These places are sites where large earthquakes often nucleate, and so would offer some of the best locations for further study and instrumentation, if a better understanding of the processes leading to failure in a large earthquake is to be achieved.

Acknowledgments. This paper benefitted greatly by discussions with Nick Christie-Blick, Hiroo Kanamori, Clarence Allen, Kerry Sieh and Lucy Jones. We thank the staff of the Caltech Seismology Laboratory and the U.S. Geological Survey in Pasadena for providing the microearthquake data. Reviews by Chris Scholz, David Simpson, Nick Christie-Blick, John Crowell and David Hill substantially improved the manuscript. We thank Kazuko Nagao for her help in drafting or annotating many of the figures. This work was funded by USGS grant 14-08-0001-G948. Lamont-Doherty Geological Observatory contribution 3978.

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(Received November 25, 1985;
revised February 10, 1986;
accepted February 10, 1986.)