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Interactions of Major Faults with the Regional Stress Field Across the Creeping Zone of the SAF and in the Bay Area: Implications for Fault Weakening Processes

Element II: Research on Earthquake Occurrence and Effects

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INTERACTIONS OF MAJOR FAULTS WITH THE REGIONAL STRESS FIELD ACROSS THE CREEPING ZONE OF THE SAF AND IN THE BAY AREA: IMPLICATIONS FOR FAULT WEAKENING PROCESSES

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Technical Abstract

We determined orientations of principal stresses around the San Andreas Fault (SAF) system in the greater San Francisco Bay Area and regions further north along the strike-slip plate boundary. Stress orientations, as well as a ratio between stress magnitudes, were determined by inversions of approximately 6000 earthquake fault plane solutions, divided into ~100 groups based on the spatial distribution of seismicity with respect to major regional fault strands (i.e., the SAF, the Hayward-Rodgers Creek-Maacama fault zones, and the Calaveras-Green Valley-Bartlett Springs fault zones). The stress orientations, while spatially variable, show several features; to describe them, it is useful to distinguish between groups of events occurring on and off the major fault strands. First, for off-fault groups, the angle between major fault strands and the maximum horizontal compression S_H decreases systematically to the north. This contrasts with the high angles of S_H found immediately adjacent to, as well as farther from, the creeping segment of the SAF in central California by *Provost and Houston* [2001]. Second, for on-fault groups, the angle that S_H makes with major fault strands changes little along strike, averaging 50° to 55° in the creeping segment, the Bay Area, and the northernmost part of our study area. Third, as in the vicinity of the creeping segment of the SAF in central California, the majority of off-fault groups, as well as the on-fault groups, are in a strike-slip, rather than thrust, tectonic regime. Finally, anomalous east-west S_H orientations are seen in the vicinity of Sutter Buttes. In the north, multiple strands of the strike-slip fault system have accumulated little slip, dip relatively shallowly and are composed of short, complex *en échelon* segments, suggesting that they originated as thrust faults in the accretionary prism associated with the Farallon subduction and have been subsequently reactivated in a strike-slip sense following the northward passage of the Mendocino triple junction. Our results, together with the geological context, suggest that the fault system is mechanically stronger with a greater effective frictional strength in the northern portion than in the creeping section of the SAF, with the Bay Area in an intermediate state. We interpret this situation to result from the evolution of the plate boundary toward lower effective frictional strength with increasing slip.

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Non-Technical Abstract

We determined the spatial distribution of stress in the greater San Francisco Bay area and in Northern California using the geometry of earthquake fault slip. The way that stresses are reoriented by the major faults of the boundary between North America and the Pacific plates changes in a rather systematic way as one goes north. The spatial distribution of both stress and fault geometries suggest that the plate boundary system is mechanically strongest in the north and that it has evolved with time as slip accumulates and the strike-slip boundary lengthens. Understanding fault mechanics will ultimately aid efforts to forecast large, damaging earthquakes.

Introduction

The level of the frictional strength of the San Andreas fault (SAF) has been a point of contention for over two decades. Many researchers have proposed that the shear stress at which the SAF slips must be very low compared to that implied by friction levels measured in laboratory experiments on many rock types (e.g., *Byerlee* [1978]). Briefly, there are two main arguments for low frictional strength of the SAF. First, a heat-flow anomaly localized around the SAF would be expected according to a steady-state conductive model of frictional heating with Byerlee friction levels, but such an anomaly is absent (e.g., *Brune et al.* [1969]; *Lachenbruch and Sass* [1980]). Second, the maximum horizontal compressive stress in central California off of the SAF has been found to lie at high angles to the fault, requiring the fault to slip at low levels of shear stress compared to those needed in the adjacent crust (e.g., *Mount and Suppe* [1987]; *Zoback et al.* [1987]). A further line of evidence that many major faults are weak follows from the need for weak faults embedded in a strong crust in various numerical modeling studies (e.g., *Bird and Kong* [1994]; *Bird* [1995]; [*Chéry et al.*, 2001]).

Questions remain about the implications of the lack of a localized heat flow anomaly on the SAF. The main issue is that advection of heat by ground water flow may play a large role in removing frictionally-generated heat. The rate of advection depends on the level of permeability in the crust, which is not well-constrained and may vary spatially with rock type, as well as with scale. The presence of fault-related topography near the SAF is also a factor, tending to promote gravity-induced ground-water flow (e.g., [*Williams and Narasimhan*, 1989]). Recently these concerns were reiterated by *Scholz and Hanks* [in press]. Given this uncertainty, as well as the large and growing catalog of microseismicity in California, thorough analysis of stress orientations around the SAF system is called for.

Here, we mention a few particularly salient studies of stress orientations in the vicinity of the SAF. A key issue is orientation of the maximum horizontal compression S_H adjacent to the fault, because this orientation indicates whether Anderson-Byerlee mechanics are allowed.

Based on a data set including fold axes, well-bore breakouts, and individual P axes of off-fault earthquakes, *Mount and Suppe* [1987] and *Zoback et al.* [1987] found S_H oriented nearly perpendicular to the SAF. They inferred from this that the SAF slips at low levels of shear stress. However, most of their data were from shallow depths relative to seismogenic depths, and only few data were located very near to the SAF. Some data were in active SAF-parallel folds. A different technique, inversions of groups of focal mechanisms, provides stress orientations at seismogenic depths and can be applied wherever sufficient seismicity has occurred. *Hardebeck and Hauksson* [1999] inverted tens of thousands of focal mechanisms in southern California, dividing seismicity according to distance from the SAF. Far from the SAF, S_H typically lies at a high angle to the fault. Across some of their transects, most notably one across the Big Bend of the SAF near Fort Tejon, they found a broad zone (20 to 40 km wide) with S_H rotated to lower angles as the SAF is approached, which they interpreted as a 20- to 40-km-wide weak zone surrounding the SAF. *Scholz* [2000] found that interpretation untenable because such a wide weak zone would rapidly extrude vertically, which is not observed. He reinterpreted *Hardebeck and Hauksson's* [1999] observation of a broad zone of rotated S_H around the Big Bend with a transpressional plate-boundary model. By making the lower crust and upper mantle very weak, this model essentially requires the upper crust to be strong. Thus, *Scholz*'s [2000] interpretation has a strong SAF in the Big Bend region and elsewhere in southern California, although the rotated zones of S_H are somewhat equivocal elsewhere in southern California away from Big Bend. *Provost and Houston* [2001] inverted thousands of focal mechanisms to determine stress orientations around the creeping segment of the SAF in central California. They found high angles of S_H (~80°) immediately adjacent to the creeping SAF, implying that the creeping segment is a narrow mechanically-weak zone, in which intrinsic friction is low or pore pressure is high.

In this research, we extended our analysis of stress orientations to portions of the strike-slip plate boundary system further north in California. In the San Francisco Bay Area, the SAF system branches into several major faults, which carry significant portions of the slip, in contrast to the situation in central California [*Brown*, 1990]. Thus the relatively young plate boundary system in northern California spans a greater width than the mature boundary in central California, and, as we will show below, appears to be mechanically stronger, suggesting that the effective frictional strength of the SAF system varies along its strike.

Method of Stress Inversion

As described in *Provost and Houston* [2001], as well as in our USGS report for FY00, groups of earthquake focal mechanisms were inverted for the orientations of the principal stresses and their relative magnitudes.

Results

The stress tensors obtained in the northern portion of our study zone show angles of 40° to 70° angles to the major fault trends and little systematic difference between the orientation of maximum compressive stress for groups of mostly on-fault compared to mostly off-faults events. These results contrast with those found in the creeping section [*Provost and Houston*, 2001], and suggest stronger, less-well developed faults in this area, consistent with the en échellon, discontinuous, east-dipping segments east of the SAF in this region, noted by *Castillo and Ellsworth* [1993].

The results obtained in the San Francisco Bay Area are more complex, but in general they show an intermediate state between that of the creeping zone [*Provost and Houston*, 2001] and the regions farther north. The complexity of the orientation of S_H in this area is probably due to the fault distribution and intersections in the area, as the SAF branches into the Calaveras fault and then the Hayward fault.

Comparison with Creeping Segment in Central California

The results found in this analysis are combined with analogous results from the creeping section [*Provost and Houston*, 2001]. Figure 1 shows the orientations of S_H

obtained from central to northern California. A difference in the pattern of the stress orientations is clearly visible from the creeping section where S_H is almost perpendicular to the fault trend, to the Garberville-Lake Mountain fault zone in the north where S_H lies closer to the trends of the major faults. For on-fault bins, S_H makes angles of 40° to 60° with major fault trends for all three regions considered. For the off-fault bins, S_H makes smaller angles to the major fault trends, from south to north along the plate boundary fault system. The off-fault stress orientations average ~ 80° from the SAF in central California, but ~55° from the major fault trends in northern California. Figure 2 shows these orientations versus the distance along the fault; from the Maacama fault zone to the north to the creeping zone in central California (see caption for details). Here, the straight lines are least squares fits and show the increasing angle between off-fault S_H and major fault trends, from northern California to the creeping zone. As in the creeping section [*Provost and Houston*, 2001], most (76%) of the tensors correspond to strike-slip regimes while a smaller proportion (23%) correspond to a thrust regime.

Implications for Variations in Frictional Strength

The stress orientations obtained from inverting groups of fault plane solutions can provide some constraints on the strength of the fault system in each area studied. These observations taken alone can only constrain the upper bounds of the coefficient of friction on the major fault segments. The variation of the orientations of S_H from the creeping zone to northern California (Figures 1 and 2) implies that this upper bound varies with latitude in central and northern California, if the same pore pressure is assumed on all major faults. In the creeping zone, *Provost and Houston* [2001] found S_H oriented at high angles (65° to 85°) to the SAF adjacent to the fault and away from it. These observations imply a low upper bound on the frictional strength (μ 0.2 according to *Lachenbruch and McGarr* [1990] figure 10.10). In northern California we find that S_H is oriented at smaller angles to the trend of major faults (~40° to 70°) and there is no major difference between the off-fault and the on-fault orientations. These observations alone imply an upper bound on the frictional strength of the major regional faults of higher value ($\mu \cong 0.6$) without excluding the possibility that they could be weak. On the other hand, our results permit an alternative explanation in which μ is everywhere near 0.6 - 0.8 but pore pressure is higher on the SAF in central California. That is, the severe misorientation of the SAF in central California can be explained by either a low coefficient of friction or high pore pressure (or by a combination of these), and stress orientations alone can not distinguish these situations.

In order to draw further implications from these stress orientations it would be necessary to make some strong simplifying assumptions about the state of stress in California. One possibility is that SAF parallel thrust faults could be regulating the normal tractions on planes parallel to the SAF, so that they are everywhere equal. If that is assumed, as well as constant normal traction across planes perpendicular to the SAF, a constant fault-parallel velocity component, and constant pore pressure, then one can infer that variations in the orientations of the principal stresses closer to the fault must be due to variations in effective frictional strength of the fault system. Specifically, the change in orientations of off-fault S_H relative to the trends of major faults would imply an increase in the effective frictional strength of the SAF system towards the north. The geological observations discussed below, regarding contrasts between central and northern California in the geometrical configuration of the strike-slip fault system, suggest that such regional variations in the effective frictional strength exist.

Relation to Tectonic History

The systematic decrease toward the north in the angle between S_H and the major faults (Figures 1 and 2) may be related to the relative youth and multiple-stranded nature of the northernmost portions of the SAF system compared to the central SAF. The plate boundary system appears progressively stronger as one goes farther north. The younger, less-developed fault strands in the north are believed to be thrust fault structures associated with subduction of the Farallon / Gorda plates, now reactivated in a mostly strike-slip sense [*Castillo and Ellsworth*, 1993]. These structures dip northeastward and get steeper toward the south becoming nearly vertical in the Bay Area (Hayward-Calaveras fault zone. The near-vertical planes are more favorably oriented for strike-slip than the shallower dipping ones. Thus, the plate boundary appears to evolve, with increasing slip, towards a geometry, and possibly a rheology, that more readily accommodates strike-slip plate motions. Although northern California may have a greater frictional strength than the creeping zone, even S_H as low as 40° to the fault still does not exhibit the optimal angle predicted for brittle failure under the Byerlee friction law [*Byerlee*, 1978].

Based on their 3D thermo-mechanical modeling of northern California, *Furlong et al.* [1989] concluded that the lithospheric boundary between the Pacific and North American plates, as well as the crustal structure in the area, must evolve as the Mendocino triple junction travels northward. They inferred that the plate boundary will tend to migrate eastward to the Maacama and Bartlett Springs fault zones.

The stress states found in northern and central California in this analysis show differences as mentioned above, but also contrast with the ones in southern California. *Hardebeck and Hauksson* [1999] determined stress orientations from focal mechanisms of southern California earthquakes. By looking at these orientations along profiles across the SAF system, they found that the maximum horizontal compression is at a high angle to the SAF in the far field, but rotates to a smaller angle as one gets closer to the fault zone. More specifically on the Mojave Desert profile in the Big Bend region, S_H rotates over a ~20-40 km wide zone in the vicinity of the SAF. Perhaps the simplest interpretation of this rotation is that the SAF is mechanically strong in the Big Bend region.

Slip partitioning and slip rates estimated along the fault system from southern California to the Bay Area, also indicate variations in the strength of the SAF along its strike [*Jones and Wesnousky*, 1992]. *Wright* [2000] segments the SAF system from north to south, according to slip rates, fault types and spacing, and the depth and distribution of seismicity. He identified five regions: the northern region, from the Mendocino triple junction to San Pablo Bay ("Juvenile"), the San Francisco Bay region ("Adolescent"), the SAF in central California ("Mature"), the Big Bend region ("Confounded"), and the southern region from the Mojave to the Salton trough ("Expanding"). It is interesting that his segmentation of the SAF system is quite consistent with the variations in stress orientations seen by the present study, *Provost and Houston* [2001], and *Hardebeck and Hauksson* [1999].

Schwartz and Hubert [1997] studied the state of stress just north of the Mendocino triple junction. By inverting 70 fault plane solutions for the stress tensor they found N-S compression in this area, nearly parallel to the strike of the subduction boundary. One of their interpretations for this stress orientation is that the southernmost section of the Cascadian subduction zone fails under very low resolved shear stress and thus is weak.

In summary, these results together suggest that the San Andreas plate boundary is a rather complex fault system with spatially-varying frictional strength that evolves over geological time as slip accumulates and as bends in the major faults develop.

Conclusions

The issue of the frictional strength of the SAF system remains controversial. Systematic analysis of stress orientations from inversions of earthquake focal mechanisms reveals spatial variations in the mechanical behavior of this major plate boundary system.

The orientations of the maximum horizontal compressive stress surrounding the San Andreas plate boundary system from central to northern California that we determined are shown in Figures 1 and 2. In the north the maximum horizontal compression makes an average angle of ~55° with major fault trends, and there is no clear difference between on- and off-fault stress orientations. These results contrast with the ones found in the creeping zone [*Provost and Houston*, 2001]. Stress orientations in the greater Bay Area show an intermediate stage between central and northern California. By themselves, these observations provide an upper bound (that increases with latitude) on the effective frictional strength of the fault system. The SAF system has evolved, following the northward passage of the Mendocino triple junction, from a young multiple-stranded plate boundary in the north, to a mature strike-slip plate boundary in the creeping zone where more total slip has occurred. Given our results, together with differences in fault continuity, dip and total slip between northern and central California, it appears likely that the effective frictional strength and mechanical behavior of the SAF system varies significantly along strike, with different characteristics in northern California, the Bay Area, the creeping segment, and southern California. In many applications it may be important to take this possible variation in frictional strength into account.

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A complete description of our research for this grant has been submitted to the Journal of Geophysical Research [Provost and Houston, 2002]. Portions of the manuscript have been used in this report.

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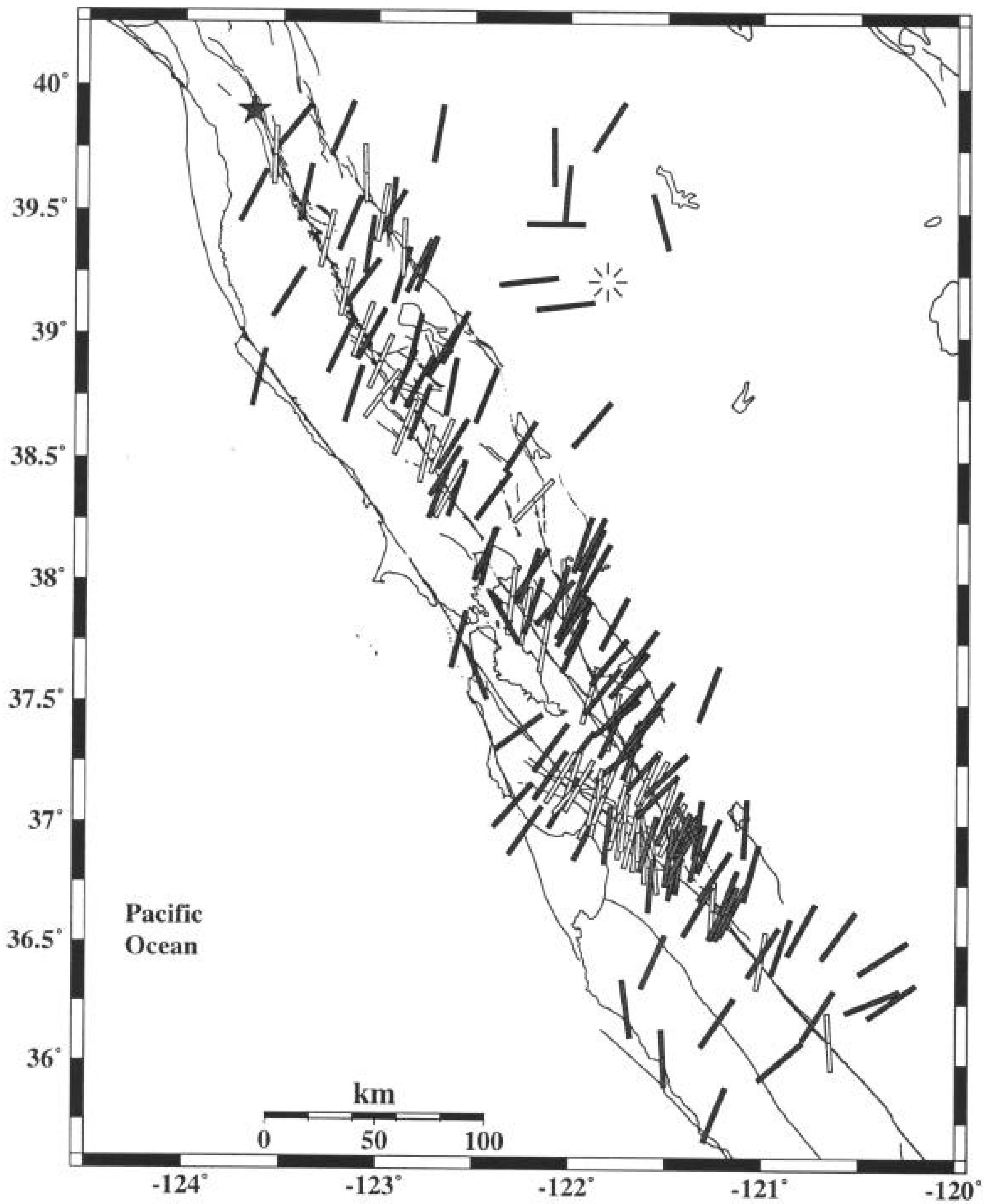

Figure 1. Orientations of maximum horizontal compression in central and northern California, from the Parkfield region to near the Mendocino triple junction. The results from our previous study [*Provost and Houston*, 2001] are combined with the ones found in this analysis to show the state of stress around much of the San Andreas plate boundary system. Light gray bars represent the stress orientations for on-fault

seismicity; dark gray bars represent off-fault orientations. The dark star (near 40° latitude) corresponds to the reference point used to construct Figure 2.

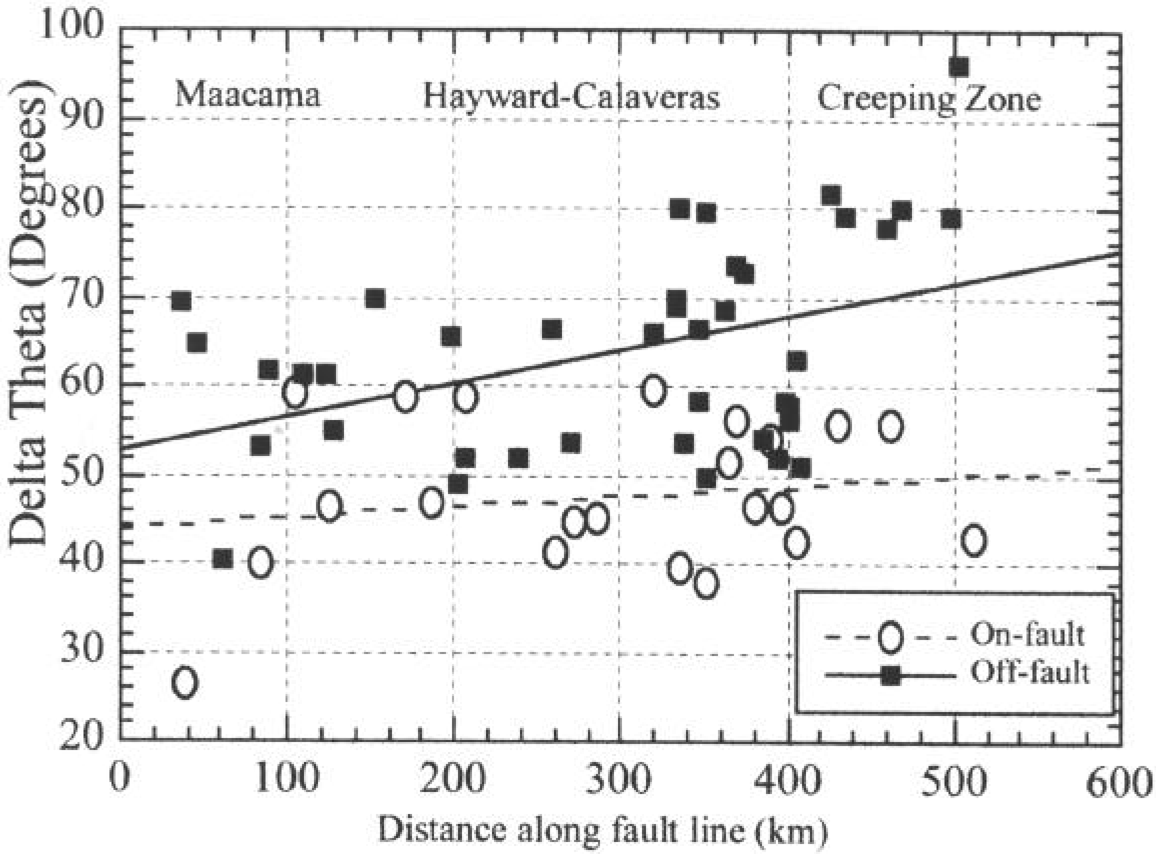

Figure 2. Orientations of the maximum horizontal compression relative to major fault trends versus distance along the fault system. As a reference line, along which to measure distance, we defined a straight line from the star in Figure 1 on the Maacama fault, running through the Rogers Creek and the Hayward faults, to the SAF-Calaveras fault junction, which then bent to follow the strike of the San Andreas fault in the creeping section. Open circles correspond to on-fault bins and closed squares to off-fault bins. The dotted and the straight lines are linear fits using the least squares' method for the on-fault and the off-fault groups, respectively.