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The state of stress near the Mendocino triple junction from inversion of earthquake focal mechanisms

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Abstract. Focal mechanisms of 70 earthquakes occurring in the region of the Mendocino triple junction between 1977 and 1995 are inverted to obtain the regional stress orientations and relative magnitudes in this tectonically complex area. A diverse set of earthquake geometries is consistent with a single stress field characterized by north-northwest, horizontal, maximum principal compressive stress. Although this stress direction is almost perpendicular to convergence between the North American and Gorda plates, it is consistent with the stress direction inferred within the Gorda plate northwest of the triple junction. A maximum compressive stress direction nearly parallel to strike of the Cascadia subduction zone implies very low resolved shear stress across this plate boundary. Evidence for failure along the southernmost section of the Cascadia subduction zone comes from the occurrence of the recent 1992 (Ms=7.1) Cape Mendocino underthrusting earthquake as well as from measurements of Holocene surface uplift consistent with the 1992 coseismic uplift pattern. Rupture of the Cascadia subduction zone under this stress regime requires that the southernmost region of the Gorda-North American Plate boundary is weak.

Introduction

Complex interaction between the Pacific, North American, and Gorda plates at the northward migrating Mendocino triple junction (MTJ) is responsible for some of the highest rates of seismic activity, surface uplift and crustal deformation in the continental United States. Although many of the fundamental ideas of plate tectonics were developed with the MTJ in mind, several aspects of plate interactions at this triple junction are poorly understood. The majority of the seismicity near the MTJ is located offshore, diffusely distributed throughout the Gorda plate [*Smith et al.,* 1993]. This diffuse seismicity represents internal deformation within the young, weak Gorda plate in response to north-south compression caused by oblique convergence between the Gorda and Pacific plates [*e.g., Silver,* 1971]. One important issue presently under contention is the degree of coupling between the Gorda and North American plates along the Cascadia subduction zone. Although the relative motion between the North American and Gorda plates near the MTJ is about 34 mm/yr in an east-northeasterly direction [*DeMets et al.,* 1990], this thrust boundary has little seismic activity and many researchers question whether subduction occurs seismically, aseismically, or at all. Analysis of seafloor magnetic anomalies led *Riddihough* [1984] to conclude that during the last 3 My, the southern portion of the Gorda plate has ceased to subduct and is moving parallel to the trench. However, observations are accumulating that suggest the Cascadia subduction zone is seismically active and well coupled. Such observations include: 1) the occurrence of the 1992 large (Ms=7.1) underthrusting Cape Mendocino earthquake; 2) geologic evidence of great subduction zone earthquakes rupturing this plate boundary in the Holocene [*e.g., Clarke and Carver,* 1992; *Merritts,* 1996]; 3) Holocene east-west shortening in the Cascadia accretionary complex north of the Eel River [*Clarke and Carver,* 1992]; and 4) 15 mm/yr of northeast directed contraction geodetically determined in the region between Cape Mendocino and Arcata Bay [*Murray et al.,* 1996]. In this paper we address the degree

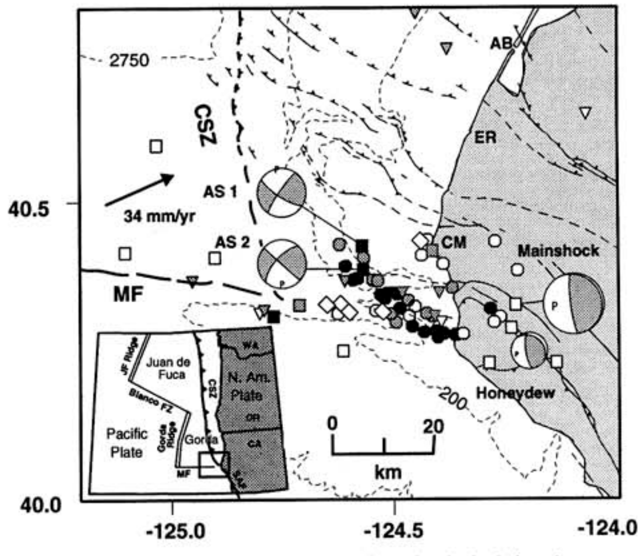

Figure 1. Location of earthquakes included in the stress inversion. Focal mechanism solutions were determined by Harvard (squares), Berkeley (inverted triangles), *Schwartz, 1995* (circles) or *Tinker and Beck,* 1995 (diamonds). Unshaded, lightly and darkly shaded symbols represent events in the depth ranges 0-14, 15-22, and 23-35 km respectively. Major faults and shear zones are from *Clarke* (1992); bathymetry is in meters, and Gorda/North America motion from *DeMets et al.* [1990]. AB is Arcata Bay, AS1 and AS2 are the largest aftershocks of the 1992 mainshock, CM is Cape Mendocino, CSZ is Cascadia Subduction Zone, ER is Eel River, JF is Juan de Fuca, and MF and SAF are the Mendocino and San Andreas faults, respectively.

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of coupling between the Gorda and North American plates in the vicinity of the MTJ. We estimate the state of stress near the triple junction through inversion of fault plane solutions, and find compelling evidence that the north-south compression dominant in the Gorda plate extends at least as far east as the onshore location of the triple junction, approximately 25 km southeast of Cape Mendocino (Figure 1). Failure of the southern Cascadia subduction zone under this stress regime implies that this fault is weak.

Inversion of Fault Plane Solutions for Stress

Fault Plane Solutions

Few well-determined fault plane solutions are available for the many small-to-moderate size earthquakes (M< 5.0) that occurred near the Mendocino triple junction prior to the April 25, 1992 Cape Mendocino, California earthquake (mainshock in Figure 1). The deployment of a portable, three-component, broadband, seismic network immediately following this large earthquake [*Schwartz,* 1992] has allowed reliable focal mechanisms to be determined for many of its aftershocks. Expansion of the Berkeley Broadband Seismic Network in northern California since 1992, has resulted in the routine determination of moment tensor solutions for all earthquakes in northern California with magnitudes greater than about 4.0 [*Romanowicz et al.*, 1993]. In this study we invert focal mechanisms from 70 events occurring between 1977 and 1995 in the area bounded between 40° and 41° N and 124° and 125.3 ° W (Figure 1).

The few large earthquakes that occurred prior to the 1992 Cape Mendocino event concentrate along a weak west-northwest linear trend (see squares in Figure 1). Harvard centroid moment tensor solutions for these events reveal that all but the August 17, 1991 Honeydew event can be characterized by strike-slip faulting with one near-vertical nodal plane striking parallel to this trend. These events most likely represent motion between the Gorda and Pacific plates along the Mendocino Fault, or occur as internal deformation within the Gorda plate.

Schwartz (1995) inverted amplitude ratios and broadband waveforms recorded by portable stations to obtain fault plane orientations and depths for 38 Cape Mendocino aftershocks with local magnitudes between 2.5 and 4.4 (circles in Figure 1). The shallowest of these events (depths less than 15 km, unshaded symbols in Figure 1) all locate within the North American plate and display a wide variety of faulting geometries, most sharing north-south, nearly horizontal pressure axes. The same north-south pressure axis orientation dominates the mechanisms in the depth ranges between 15-22 km and greater than 23 km but there is more consistency in the orientation of the nodal planes for events in these depth ranges. Seven out of ten events in the intermediate depth range share thrust motion on a south-southeast shallowly dipping nodal plane. *Schwartz* (1995) favored an interpretation that called for underthrusting of the Gorda Plate beneath the Pacific plate; however, she also recognized that these events could be occurring within the Gorda plate in response to regional north-south compression. All events in the deepest range as well as ten of fourteen Berkeley centroid moment tensor solutions for events following the Cape Mendocino mainshock by at least one month (inverted triangles in Figure 1) indicate strike-slip mechanisms with near-vertical nodal planes striking west-northwest and north-northeast. The locations and depths of these events suggest that they occur either within the Gorda plate or between the Gorda and Pacific plates along the Mendocino Fault. Focal mechanisms for four of the five moderate-sized aftershocks of the Cape Mendocino earthquake determined by *Tinker and Beck* [1995] consist of very shallow (5 km or less), northwest striking, 45° dipping nodal planes and are very different from most of the other mechanisms examined in this area (diamonds in Figure 1). *Tinker and Beck* [1995] interpreted these events as representing failure on thrust faults in the accretionary prism in response to northeast compression due to Gorda plate subduction. A summary of pressure and tension axes for all 70 events is shown in Figure 2a. The wide distribution of pressure and tension axes reflects the diversity of fault plane solutions that occur in this region.

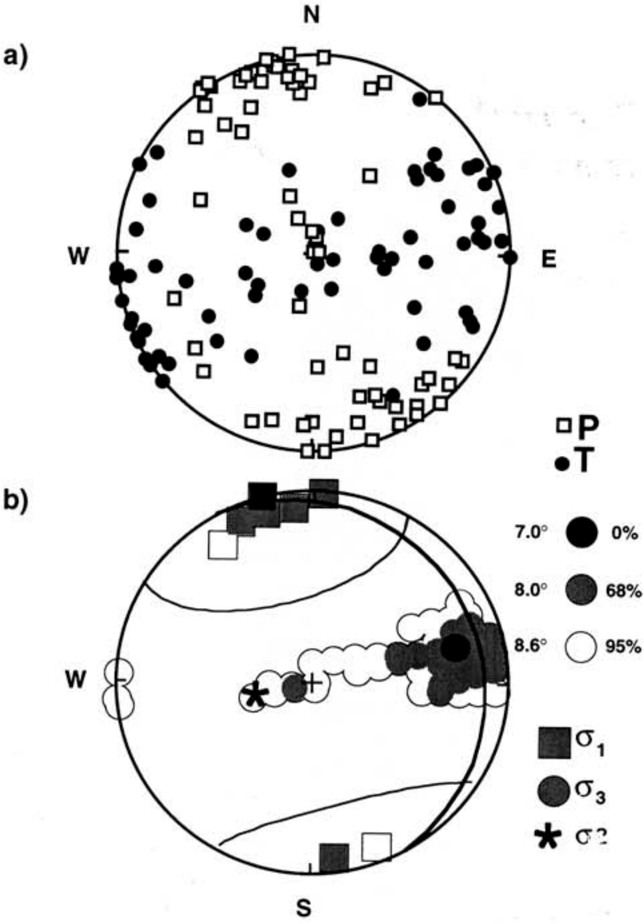
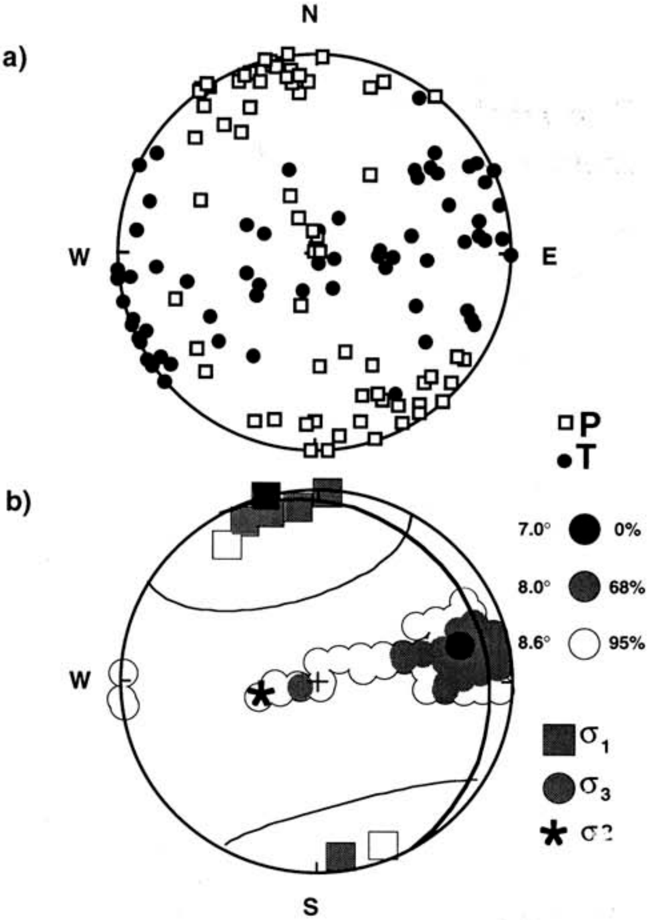


Figure 2. Lower hemisphere stereonet plots of (a) pressure (P) and tension (T) axes for all earthquakes used in this study and (b) the distribution of acceptable σ_1 and σ_3 orientations having average misfit values associated with three confidence limits. The 0% confidence limit indicates the best-fitting solution, the σ_2 direction for this model is also indicated. The thin arcs show the region of the stereonet over which σ1 was searched in the fine grid search. The thick great circle represents the orientation of the fault plane of the 1992 Cape Mendocino earthquake.

Inversion Method and Results

We use the method of *Gephart and Forsyth* [1984] to invert the focal mechanisms of these 70 events for the regional stress tensor. Inversion of slip directions can only resolve four of the six components of the stress tensor. These are of coupling between the Gorda and North American plates in the vicinity of the MTJ. We estimate the state of stress near the triple junction through inversion of fault plane solutions, and find compelling evidence that the north-south compression dominant in the Gorda plate extends at least as far east as the onshore location of the triple junction, approximately 25 km southeast of Cape Mendocino (Figure 1). Failure of the southern Cascadia subduction zone under this stress regime implies that this fault is weak.



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Inversion Method and Results

We use the method of *Gephart and Forsyth* [1984] to invert the focal mechanisms of these 70 events for the regional stress tensor. Inversion of slip directions can only resolve four of the six components of the stress tensor. These are only about 5% of lithostatic pressure to match observed heat flow measurements. They speculated that high pore fluid pressure and low friction can account for these low shear stresses. *Magee and Zoback* [1993] suggested that the northern Japan subduction zone has low frictional strength based on their determination that the minimum principal stress direction acts nearly perpendicular to the fault plane. Like *van den Beukel and Wortel* [1987], both *Magee and Zoback* [1993] and *Wang et al* ., [1995] suggest that the lack of fault strength may be attributed to elevated pore fluid pressure.

The early recognition that the San Andreas Fault is weak [*e.g.*, *Brune et al.,* 1969] and the mounting evidence that other active fault zones may also be sliding in response to low resolved shear stress, has stimulated much research on the mechanical behavior of faults. Several mechanisms capable of reducing fault strength have been proposed with the most promising including the existence of pressurized fluids in the fault zone (*e.g.*, *Byerlee*, 1993; *Sleep and Blanpied*, 1992) and dynamical models such as acoustic fluidization [*Melosh*, 1996]. An important aspect of many of these models is that the elevated fault zone pressure required for failure is transient and cyclic, existing only long enough for slip to occur on the fault which restores pressure to a lower value. For the fluid pressurization models, compaction processes active between earthquakes increase fluid pressure permitting frictional failure to occur cyclically at relatively low shear stress. This aspect of weak fault models is particularly attractive for explaining our observations of few, if any, aftershocks of the 1992 Cape Mendocino earthquake occurring on the plate interface that broke during the mainshock. If slip on the thrust interface during the mainshock increased fault zone porosity and reduced fluid pressure to near hydrostatic, the low resolved shear stress on the Cascadia subduction zone plate boundary would no longer be large enough to cause failure generating aftershocks with similar mechanisms. In essence, the fault would lock up after slipping in the mainshock and not move again until fluid pressure increases to near lithostatic.

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