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ENIGMA OF EARTHQUAKES AT RIDGE-TRANSFORM-FAULT PLATE BOUNDARIES - DISTRIBUTION OF NON-DOUBLE COUPLE PARAMETER OF HARVARD CMT SOLUTIONS

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Abstract. The distribution of the non-double couple parameter of shallow earthquakes reported in the Harvard CMT catalogue shows systematic characteristics depending on the epicentral locations and types of fault mechanisms. We suggest that they can be explained by the presence of subevents with different double couple mechanisms in a single rupture sequence. The earthquakes at the ridge-transform-fault plate boundaries show a particularly interesting pattern. It is suggested that two types of faulting expected in the area (i.e., normal faults at ridges and strike slip faults at transform-faults) tend to occur almost simultaneously, although this hypothesis needs to be delineated by careful analyses using bodywave waveforms.

Introduction

Following the deployment of global digital seismic networks in the 1970's and 1980's, it has now become very common to parameterize earthquake source mechanisms using a moment tensor (MT), instead of the conventional double couple (DC) model. A good example is the routine determination of the centroid moment tensors (CMT) by the Harvard group [e.g., Dziewonski et al., 1981]. Hundreds of new mechanism solutions are reported every year [e.g., Dziewonski et al., 1984] and in the future the catalogue will be increasingly used to constrain the dynamics of the Earth. Interesting statistical characteristics of the Harvard CMT (HCMT) solutions are often reported by the Harvard group [e.g., Ekström and Dziewonski, 1988]. A MT representation of seismic sources has extra degrees of freedom compared to a DC modeling. It has not been, however, much discussed by the Harvard group about what new informations we are really obtaining using moment tensors.

Since the isotropic component is constrained to be zero in the HCMT solutions, the deviation of a moment tensor from DC can be described by a single parameter, $\varepsilon \equiv -\lambda_2/\max(|\lambda_1|,|\lambda_3|)$ where $\lambda_1,\lambda_2,\lambda_3$ ($\lambda_1\geq\lambda_2\geq\lambda_3$) are eigenvalues of MT. $\varepsilon=0$ for a DC mechanism, and takes a value between -0.5 and 0.5 for a deviatoric MT. Positive or negative value of ε corresponds to the predominance of tensional or compressional principal axis, respectively. For deep earthquakes there is an apparent correlation between the stress state of the down-going slab and the sign of ε [Giardini, 1983; Kuge, 1991]. In this report, we will show that for shallow earthquakes, ε of the HCMT solutions exhibits distinct patterns depending on the epicentral location and the type of faulting mechanism.

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Distribution of ε

The HCMT catalogue used here consists of 5481 shallow (<50km) earthquakes that occurred between Jan. 1977 and Sept. 1989. The average ε value ($\bar{\varepsilon}$) for all earthquakes is almost zero, $\bar{\varepsilon}=-0.002(\pm0.002)$ (Table 1), and the distribution of ε is very much Gaussian. So at the first look, the histogram of ε appears to suggest that shallow earthquakes can be well described by DC models ($\varepsilon=0$) and that the size of non-double couple (NDC) parameter ε simply reflects the un-modeled random error in the inversion process. We show below that it is not the case.

TABLE 1. Averag ε ($\bar{\varepsilon}$)

	Sub-duction	RTF	Other Inter-plate	Intra-plate	Whole Earth
All Mecha-nism	-0.024 ±0.002 (3366)	0.057 ±0.004 (1085)	0.006 ±0.007 (628)	0.007 ±0.008 (402)	-0.002 ±0.002 (5481)
Normal Fault	0.035 ±0.008 (400)	0.056 ±0.008 (329)	0.113 ±0.020 (64)	0.037 ±0.021 (65)	0.049 ±0.005 (858)
Thrust Fault	-0.060 ±0.003 (1479)	-0.055 ±0.043 (25)	-0.033 ±0.014 (116)	-0.009 ±0.014 (112)	-0.055 ±0.003 (1732)
Strike Slip	0.020 ±0.008 (389)	0.062 ±0.005 (615)	0.001 ±0.011 (225)	0.002 ±0.017 (89)	0.035 ±0.004 (1318)

Numbers in parentheses are the numbers of earthquakes in each group. Normal fault and thrust fault are defined by the condition that P- and T-axis is located within 30 degrees from the vertical, respectively, and a strike slip is defined by the condition that both P- and T- axes stay in 30 degrees from the horizontal plane.

Plate Boundary

We first classify earthquakes into four categories according to their epicentral locations. The four classes are events (1) at the subduction zones, (2) at the ridge-transform-fault (RTF) boundaries, (3) at other plate boundaries, and (4) intra-plate events. Each event is classified into one of the three plate boundaries if it is located within 5 degrees from the boundary (if there is more than one plate boundary within 5 degrees, the closest one is chosen), and if it does not belong to any of the three, it is classified as an intra-plate event. Digitized plate boundary data are taken from the Hypermap program (R. L. Parker).

The first row of Table 1 shows the average ε for each group. $\bar{\varepsilon}$ of subduction zone and RTF earthquakes are significantly different from zero. Figure 1a compares the distribution of ε of those two regions. The difference of

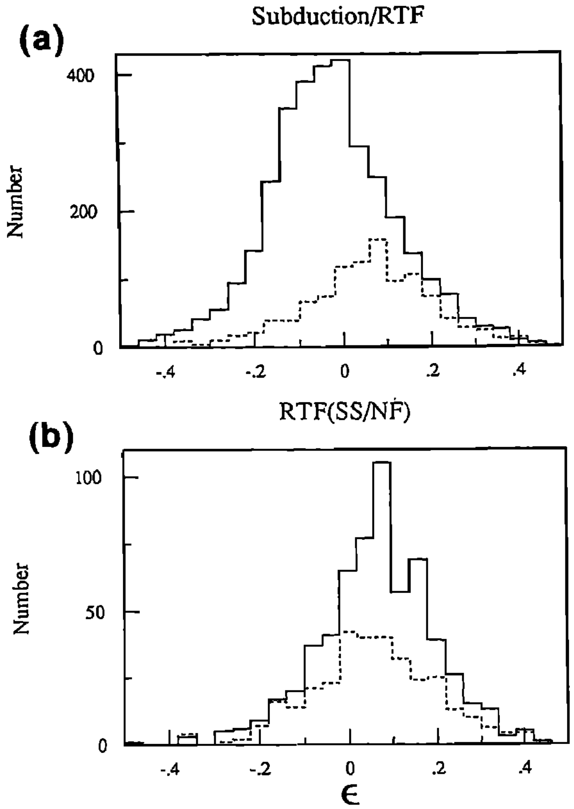

Fig. 1. Histogram of ε distribution. (a) Solid and broken lines are for subduction zone and RTF events, respectively. (b) Solid and broken lines are for strike skip and normal fault events at RTF boundary, respectively.

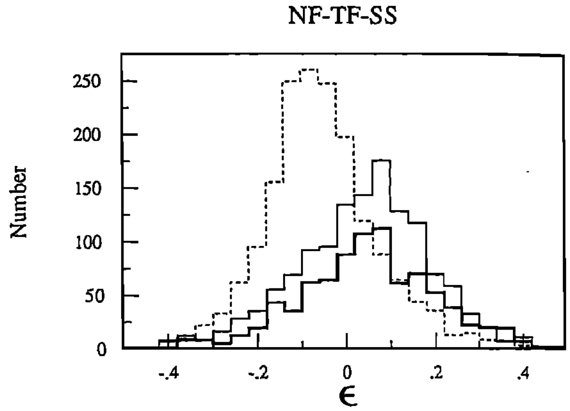

Fig. 2. Comparison of ε distributions of normal fault (thick solid line), thrust fault (broken line) and strike slip (thin solid line) events.

two distributions is obvious. For the subduction zone events, ε is shifted to negative values, which corresponds to the predominance of compressional principal axis, and for the RTF boundary events, ε is shifted to positive values, which corresponds to the predominance of tensional principal axis. This contrast of NDC distribution in these areas seems to be consistent with the idea of plate tectonics, which defines these two boundaries as convergent and divergent boundaries. The positive shift of the RTF boundary events is especially large and should reflect something real.

Since ridges and transform faults are two different kinds of plate boundaries characterized by two different types of earthquakes, events there are further classified into strike-slip (SS) and normal fault (NF) events (Table 1, Figure 1b). They both have the similar positive ε shift.

Mechanism Type

We then classify the HCMT solutions by their mechanism types. A normal fault, a thrust fault and a strike slip are defined by the location of principal axes (see the caption of Table 1). Figure 2 compares the distributions of ε for three types of mechanisms. Here we observe the variation of ε distribution; thrust events show a negative shift of ε and normal fault and strike slip events show positive shifts. The positive ε shift of subduction zone events (Figure 1a) can be now understood as the result of the positive ε shift of thrust events, since they are the most abundant type of earthquake in the area. Table 1 summarizes all results. Normal fault events appear to have significant positive ε shifts in all regions, while for thrust fault and strike slip events the shifts are mostly restricted to subduction zones and RTF, respectively.

Discussion

It is very difficult to reconcile the ε shifts observed in Figure 1 and 2 and Table 1 as the result of un-modeled random errors in the inversion processes. Such errors, of course, exist but it is difficult to think that they cause such strong systematic ε shifts.

The positive and negative shifts of ε-value of normal and thrust fault events can be explained by the presence of multiple subevents with different DC mechanisms in a single rupture sequence. These situations can be expected if the stress state in the source region is dominated by either minimum (normal fault) or maximum (thrust fault) principle stress axis laying in a near horizontal direction. If this condition is satisfied, a normal or thrust fault event may be followed by a strike slip subevent which has T- or P-axis

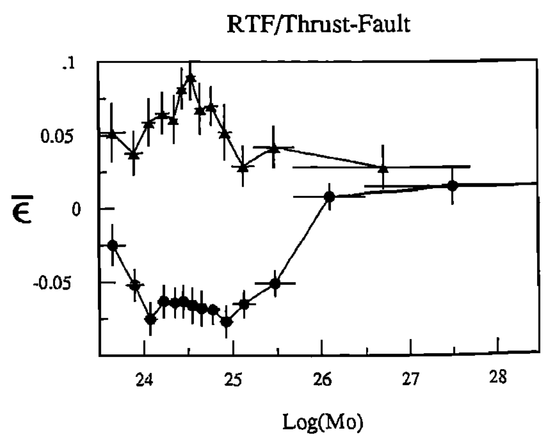

Fig. 3. Earthquake size dependence of $\bar{\varepsilon}$ for the RTF (triangle) and thrust faults (circle) events. The vertical error bars indicate one standard deviation of $\bar{\varepsilon}$ estimate.

in the same direction with that of the normal or thrust fault subevent, respectively. The 1988 Armenia earthquake is such an example; in this case a strike slip event is followed by a thrust event, resulting in a CMT solution with ε=-0.20 [Satake et al., 1989]. For deep earthquakes, similar examples are given by Kuge and Kawakatsu [1990] and Kuge [1991] for both downdip compressional and tensional events.

Figure 3 shows the size dependence of $\bar{\varepsilon}$ for RTF events and thrust fault events. Both groups indicate consistent large deviations from DC, except for very large (M_o>≈10^{26}dyn·cm) events. If our explanation of ε shifts is correct, this suggests that large events occur on large, flat fault planes, while smaller events are more complicated.

Enigma of Earthquakes at RTF Plate Boundaries

At RTF, the deviations from a DC for both normal fault and strike slip events are more pronounced than their average and they seem to need a special attention. When a significant NDC component of MT is observed, there appear to be three possible explanations. The first explanation is to attribute it to the near source structure. Here we consider the near source anisotropy. If the source region is very anisotropic, even a simple DC earthquake can be observed as MT with a large NDC component [Kawasaki and Tanimoto, 1981]. Since seismic observations often indicate faster seismic velocities in the spreading direction compared to other directions, such an anisotropic structure can be a candidate to explain the observed shift of ε for events at the RTF boundaries. However, such an axisymmetric structure does not seem to explain the systematic ε shift observed for strike-slip events. This is because if a right lateral strike-slip event is observed as a NDC moment tensor with a positive ε-value due to the axisymmetric near source anisotropy, a left lateral strike-slip event should be observed as a NDC moment tensor with a negative ε-value due to the same near source anisotropy. There is no significant difference in ε distributions of right lateral and left lateral strike slip events at RTF. So we do not expect the systematic ε shift observed in the HCMT solution for strike slip events (Figure 1b) and it is unlikely that this is the primarily explanation for the ε shift.

The second explanation is that something essentially different from an ordinally DC earthquake is occurring in the region. Since the area is a region of high volcanic activities, we can easily imagine the possibility of a magmatic intrusion process occurring there. The fluid intrusion model suggested by Julian and Sipkin [1985] produces a pure horizontal CLVD mechanism with positive ε (0.5) and may explain the positive ε shift of normal fault type events near the ridge axis. It is, however, unlikely that this model explains the ε shift of strike slip events.

The third explanation is that two different types of earthquakes usually expected in the region, a normal fault at ridges and a strike-slip at transform faults, tend to occur simultaneously. If two types of events occur almost simultaneously, the CMT inversion using long-period data cannot distinguish them and resulting MT would be the summation of two DC's. As shown in Figure 4, the combination of a normal fault and a strike slip expected around

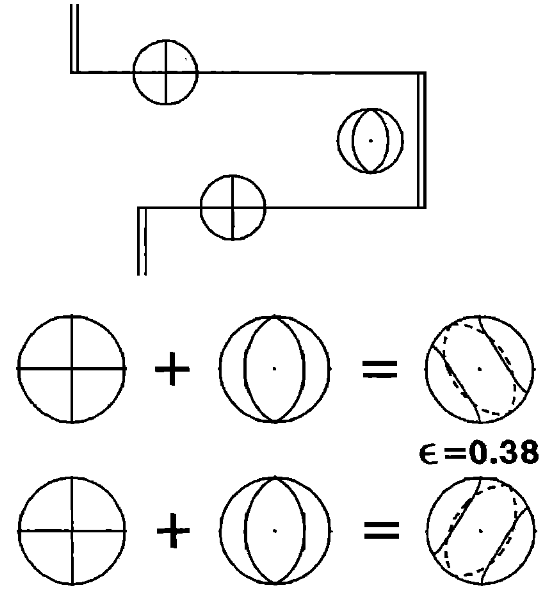

Fig. 4. Schematic figure showing typical focal mechanisms at RTF. A summation of these two types of mechanism always results in a NDC moment tensor with a positive ε.

RTF always result in MT with a positive ε-value. We think this is the most likely explanation of the observation, although it should be delineated by careful analyses using shorter period bodywave waveforms. The recent detailed mapping of the RTF topography has revealed that the mid-oceanic ridges have different level of segmentations [MacDonald et al., 1988]. It may be that the RTF system is more segmented seismogenically than we think.

Effect of systematic regional heterogeneities

It may be possible that systematic regional 'bias' occurs for different tectonic regimes due to the presence of systematic regional velocity heterogeneities. For example, at ridges, there may be strong low velocity anomalies along the ridge strike, and relatively fast material in the spreading direction. For a normal fault event near the ridge axis, this heterogeneity gives fast velocities for the compressional quadrants and slow velocities for the dilatational quadrants. For a strike slip (either right-lateral or left-lateral) event at the transform fault, it also gives the same pattern of seismic velocity variation (i.e., fast compressional quadrants and slow dilatational quadrants). It may be, then, possible that this velocity heterogeneity gives the systematic positive ε shifts for RTF events. In subduction zones, a fast velocity is expected in the slab direction and a slow velocity is expected in the direction of the mantle wedge above the slab. For a typical thrust event there, this heterogeneity gives fast velocities for the compressional quadrants and slow velocities for the dilatational quadrants; the same pattern as the RTF events, which may result in a positive ε shift. Since the observed ε shift is negative for subduction zone thrust events, this type of systematic regional heterogeneities does not seem to consistently explain the ε shifts observed in subduction zones and RTF boundaries.

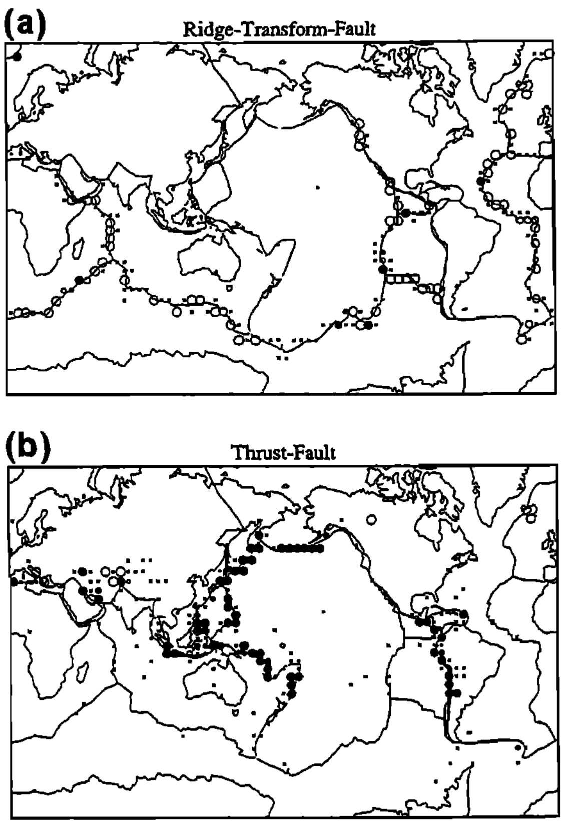

Fig. 5. Regional variation of ε distribution for the RTF (a) and thrust fault (b) events. $\bar{\varepsilon}$ is calculated for each 5°×5° block. Open and closed circles correspond to positive and negative values. The size of symbol is proportional to the $|\bar{\varepsilon}|$ and the largest symbol is for $|\bar{\varepsilon}|>0.05$. Cross marks are for blocks whose $|\bar{\varepsilon}|<0.01$ or which have the number of events less than three.

Figure 3 shows that large ε shifts are observed for smaller (Log(Mo)$\lesssim$25.5) events. For these events, HCMT solutions are determined using only long-period bodywaves, which contain many different bodywave phases, and it is difficult to predict exactly how regional heterogeneities may bias ε distributions for different tectonic regimes. So it may be still possible that the systematic regional heterogeneities suggested above could cause the observed systematic ε shifts.

Summary

Figure 5 shows the distribution of $\bar{\varepsilon}$ for the RTF and thrust fault earthquakes. It shows very distinct patterns; i.e., RTF events tend to have positive ε and thrust fault events tend to have negative ε. It seems clear that the NDC component of the Harvard CMT solution have some geophysical significance. Although we prefer the model of the presence of multiple subevents with different DC mechanisms, other models may explain the observation as well. Further detailed studies appear to be necessary to figure out what model really explains these observations.

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