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The Alignment of Earthquake T-Axes with the Principal Axes of Geodetic Strain in the Aegean Region

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Abstract: The relation between the orientations of the T-axes of earthquakes occurring within the continental crust of the Aegean, and the orientations of the principal axes of geodetic strains is examined. It is shown that the T-axes align with the principal horizontal extension axes to a degree that is unlikely to have arisen by chance, and it is concluded that the seismic deformation of the region is consistent with the response of a quasi-continuous medium to a stress regime that is organised on a regional scale.

Key Words: earthquake, T-axes, geodetic strain, Aegean region

Ege Bölgesindeki Depremlerin T-Eksenleriyle Asal Jeodetik Yamulma Eksenlerinin Dizilimi

Özet: Ege bölgesindeki kıta kabuğu içerisinde oluşan depremlerin T-eksenlerinin konumu ile jeodetik yamulmanın asal eksenlerinin konumu arasındaki ilişki araştırılmıştır. T-eksenlerinin asal yatay uzama eksenleri ile rasgele olmayan bir dereceyle sıralandığı gösterilmiştir. Böylece bölgenin sismik deformasyonunun, yarı-sürekli bir ortamın bölgesel bir ölçekte oluşturulmuş bir gerilme rejimine tepkisiyle uyumlu olduğu ortaya konmuştur.

Anahtar Sözcükler: deprem, T-ekseni, jeodetik yamulma, Ege bölgesi

Introduction

Despite more than 30 years of intense study, there is still fundamental uncertainty concerning the mechanics of continental deformation. One view regards the continents as consisting of small rigid plates, which are separated by narrow planes of weakness that penetrate the entire lithosphere. At the other extreme, the continents are regarded as continuous media undergoing distributed strain at depth, with discontinuous deformation being localised into faults or narrow shear zones only in the upper crust.

In one of the seminal papers in the study of continental kinematics and dynamics, Molnar *et al.* (1973) showed that the slip vectors of the major earthquakes occurring in Asia do not exhibit any simple grouping of orientations, such as would be expected if the tectonics of the region were dominated by the relative motions of a small number of rigid plates. In contrast, however, the P-axes of the earthquakes (which correspond to the principal horizontal shortening directions for the strain that the earthquakes represent) do exhibit a simple pattern, with the shortening direction being generally parallel to gradients of the topographic slope. The purpose of this note is to carry out a study equivalent to that of Molnar *et al.* (1973) in the Aegean realm; the principal advantage of the present study is that the slip vectors and strain axes of the earthquakes may be compared with geodetic strain measurements of the region.

Strain Field

This study uses the geodetic measurements of Billiris *et al.* (1991), Cocard *et al.* (1999), Davies *et al.* (1997), and McClusky *et al.* (2000), which span the region with a spacing of, typically, a few tens of kilometres between measurement points. The displacements are measured over time intervals of a few years in the studies of Cocard *et al.* (1999) and McClusky *et al.* (2000) and over approximately 100 years in the studies of Billiris *et al.* (1991) and Davies *et al.* (1997), who used GPS to reoccupy monuments of the Greek first-order triangulation of the 1890s. The time-averaged velocities measured in these studies are shown in Figure 1. Because of different assumptions about reference frame and scale between the different surveys, and because I am interested in the relations between the principal axes of geodetic strain and the corresponding axes of the focal mechanisms of earthquakes, I pay no further attention to the velocities themselves, but use them to estimate the strain-rate field of the region.

For each separate set of velocities, a triangular mesh was formed from the locations of the measurement sites, and for each triangle within that mesh the velocity differences between the stations at the vertices were used to estimate the average gradients of horizontal velocity across the triangle. This procedure yields a set of estimates of the velocity gradients, in an irregularly spaced distribution that is determined by the configurations of the different geodetic networks. These estimates were then smoothed onto a regular grid of spacing 0.4° E–W x 0.33° N–S (approximately 35 km) using the minimum-curvature routine of Wessel & Smith (1995). Velocity gradients, and hence the principal axes of strain rate, were obtained from finite differences of

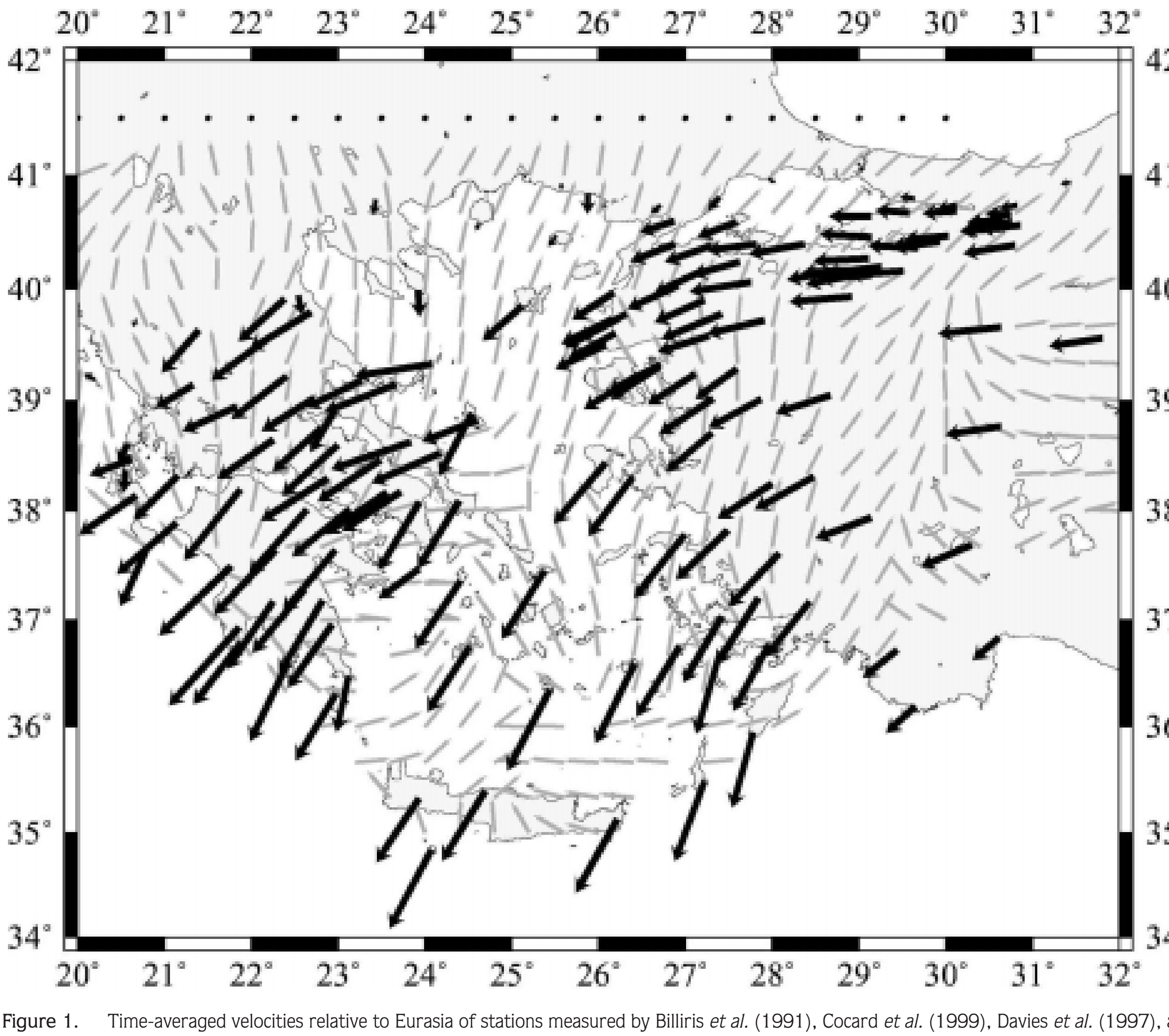

Figure 1. Time-averaged velocities relative to Eurasia of stations measured by Billiris *et al.* (1991), Cocard *et al.* (1999), Davies *et al.* (1997), and McClusky *et al.* (2000) are shown as black arrows. The longest arrow corresponds to a velocity of 40 mm/yr. Grey bars show the orientations of maximum horizontal extensional axes, calculated from these velocities as described in the text.

the gridded velocities. In what follows, only the orientations of maximum horizontal extensional strain rate are used. Uncertainty in these orientations is hard to quantify. Propagation of the formal uncertainties in the GPS measurements would yield a misleading small uncertainty in comparison with the principal sources of uncertainty which derive from the inhomogeneous distribution of data, from the choice of smoothing procedure, and from the extent to which GPS measurements fail to capture the regional crustal strain field. The influence of the last of these factors is unknowable. The influence of the other two factors was investigated by making a number of different choices of smoothing interval and of origins for the smoothing grid; on the basis of these, I estimate that any one orientation of principal axis is uncertain by ±20°. Figure 1 shows the velocities used in this study, and the orientations of the principal horizontal extension axes derived from them; these orientations resemble those of the extensional principal axes of Kahle *et al.* (2000).

The earthquakes used in this study are shown in Figure 2. Mechanisms are from Ambraseys & Jackson (1990), Jackson & McKenzie (1998), Taymaz *et al.* (1990), and from the Harvard CMT catalogue, using only those earthquakes with moment magnitude greater than 5.8. Earthquakes from the studies of Jackson & McKenzie (1998) and Ambraseys & Jackson (1990) that occurred earlier than 1965 are excluded, with the

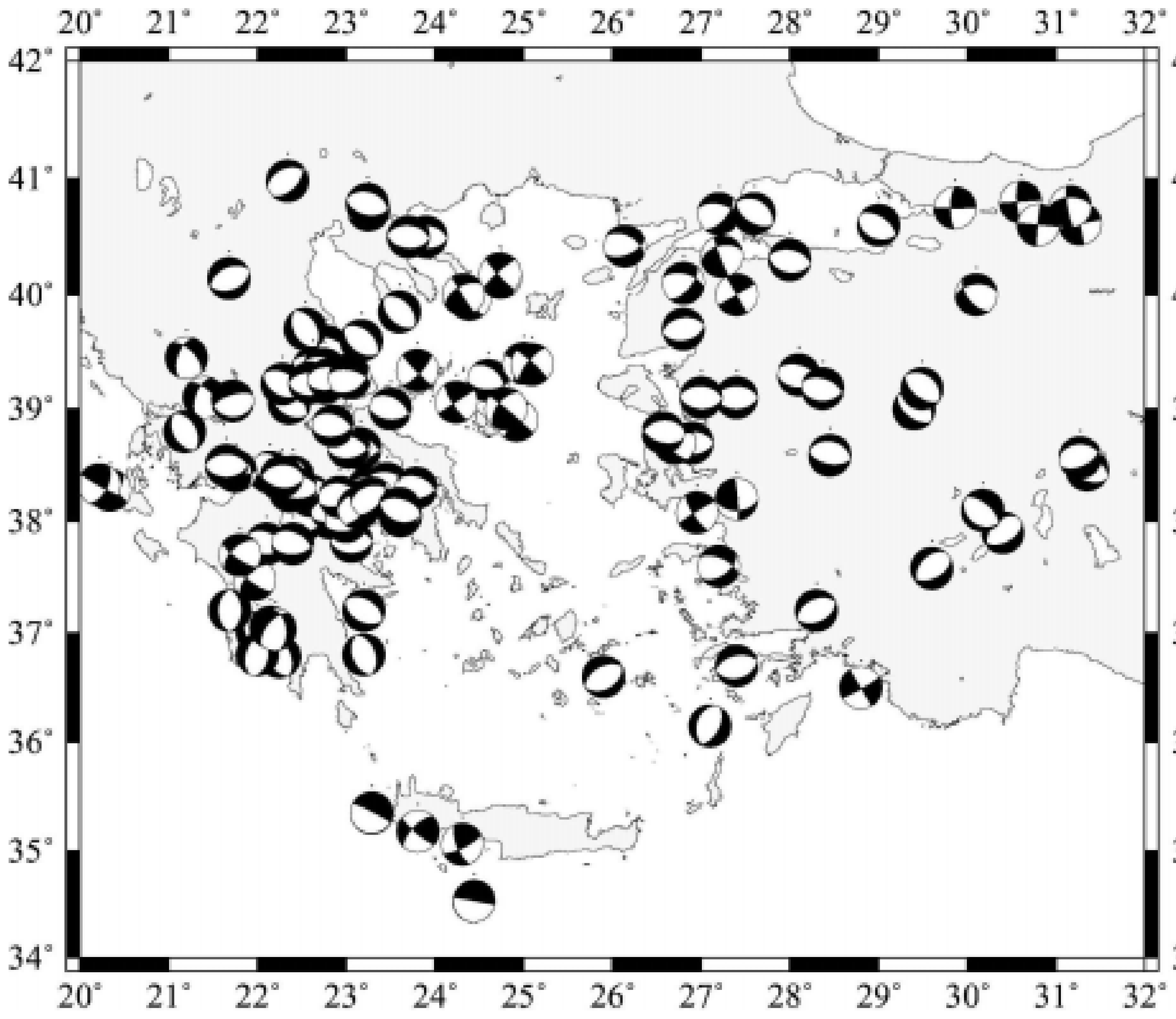

Figure 2. Focal mechanisms of earthquakes used in this study.

exception of the 1956, M=7.4, Amorgos earthquake (25.9°E, 36.6°N), which was the largest normal-faulting event in the past 100 years in the region, and which occurred in the southern Aegean, a place often regarded as part of a rigid block (e.g., Le Pichon *et al.* 1995; McClusky *et al.* 2000).

Figure 3 shows the orientations of the slip vectors of the earthquakes used in this study; the focal mechanisms given by the Harvard CMT project were excluded, except when the fault plane is known from other observations. The orientations of the slip vectors show two maxima: the higher is roughly N–S, and corresponds to the slip vectors of the large number of approximately E–W normal faults of the region. The lower maximum corresponds to the slip vectors of the predominantly right-lateral, E–W-to-NE–SW strike slip-faults in northwest Turkey and the northern Aegean.

Figure 4 shows the orientations of the T-axes of the earthquakes (corresponding to the principal horizontal elongation of the strain that they represent). First, it is clear that, although both the slip vectors and the T-axes exhibit a fairly strong alignment, the scatter in orientation of the T-axes is much less than in the orientation of the slip vectors (Figure 5). Secondly, the T-axes of the earthquakes are aligned to a remarkable degree with the principal horizontal extension axes of the geodetic strain (Figure 4). Over 60% of the T-axes are aligned to within 20° with the orientation of the maximum horizontal extensional direction; this relation holds not only for extensional faulting, but also for strike-slip faulting. The majority of the earthquakes for which this relation does not hold lie in the region of northwest Greece, where the strain is poorly constrained by geodetic observation.

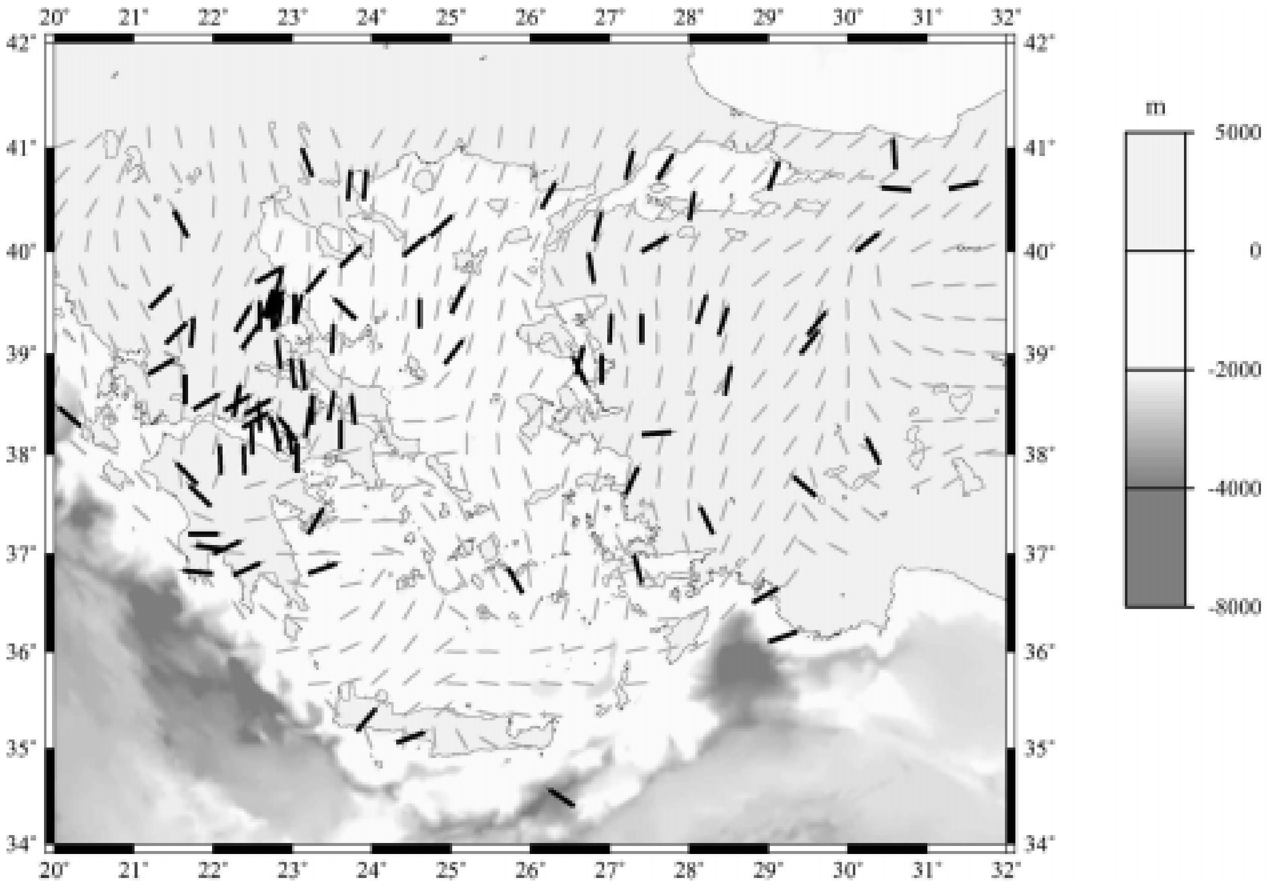

Figure 3. Horizontal projections of slip vectors of the earthquakes used in this study (Figure 2). Shades show surface height, and bars depict orientations of principal horizontal elongation (Figure 1).

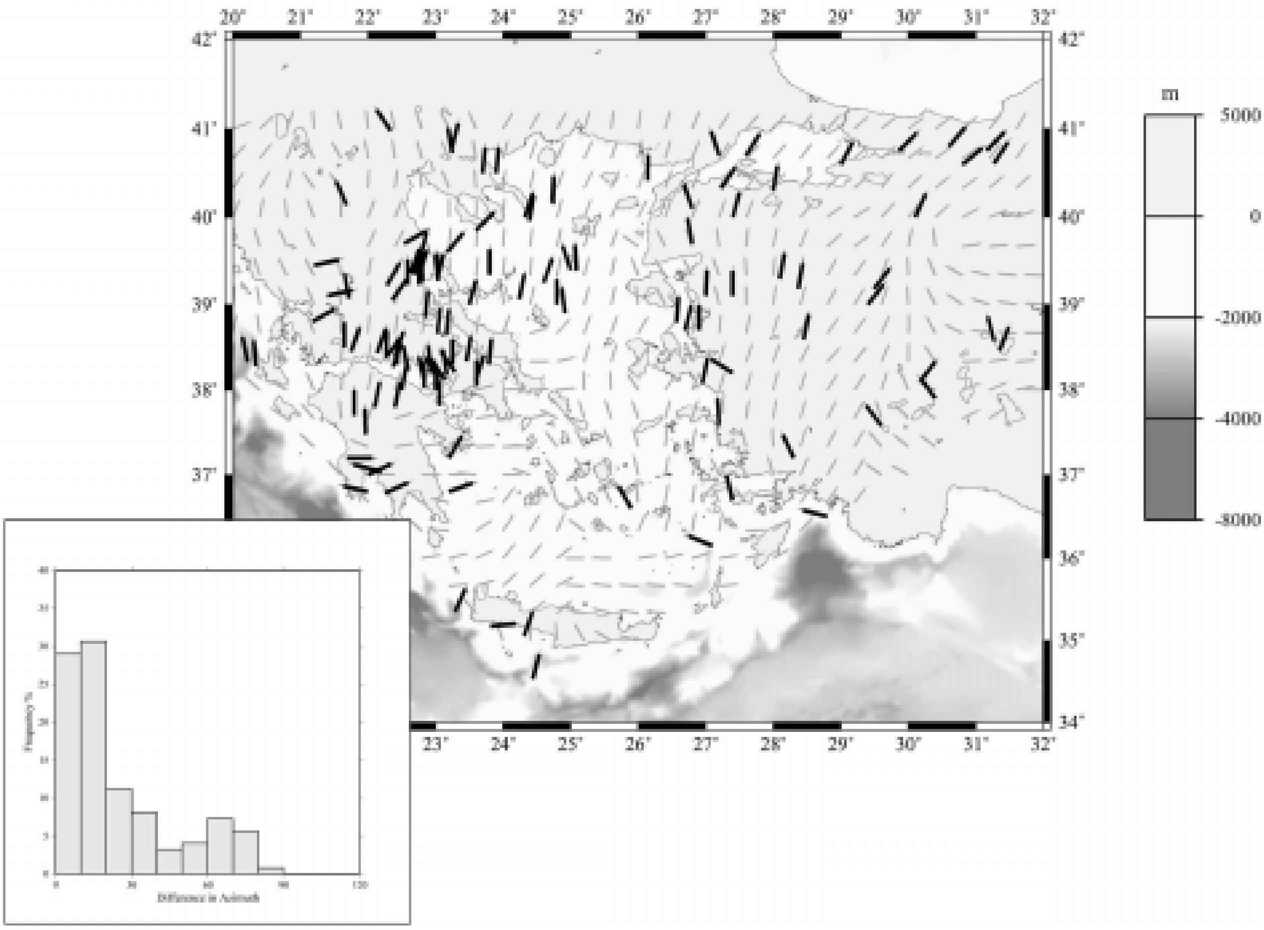

Figure 4. Horizontal projections of T-axes of earthquakes used in this study (Figure 2). Shades show surface height, and bars depict orientations of principal horizontal elongation determined by geodetic measurement (Figure 1). Inset shows distribution of the differences between the orientations of the T-axes of earthquakes in the Aegean region and the orientations of the principal horizontal extensional strain in the neighbourhood of each earthquake, as determined by geodetic measurement.

The correlation coefficient between the orientations of the T-axes of the earthquakes and the orientations of the principal horizontal extension axes of the geodetic strain at the locations of the earthquakes is 0.62, which, for 124 observations, has a probability of less than 10^{-12} of arising by chance. (The non-parametric Spearman rank-correlation coefficient is 0.46, which has a probability of less than 10^{-6} of arising by chance.) Taken together, the observations shown in Figures 4 and 5 strongly suggest that there is a unifying pattern to the seismicity of the Aegean region, in which the T-axes of the earthquakes are aligned with the extensional axes of the geodetic strain.

Discussion and Conclusion

Molnar *et al.* (1973) drew two inferences from their observation that P-axes of earthquakes in Asia show a simple alignment, while their slip vectors do not. First, the characteristic of the deformation in Asia is that the strain is organised in a simple fashion and since, by definition, plates do not strain, Asia cannot be a plate. Secondly, the fact that the strain appears to be governed by gradients of topography lends strong support to the suggestion that the lithosphere of the continents deforms in response to gradients in gravitational potential energy arising from isostatically compensated variations in its density structure (e.g., McKenzie 1972; Molnar & Tapponier 1978).

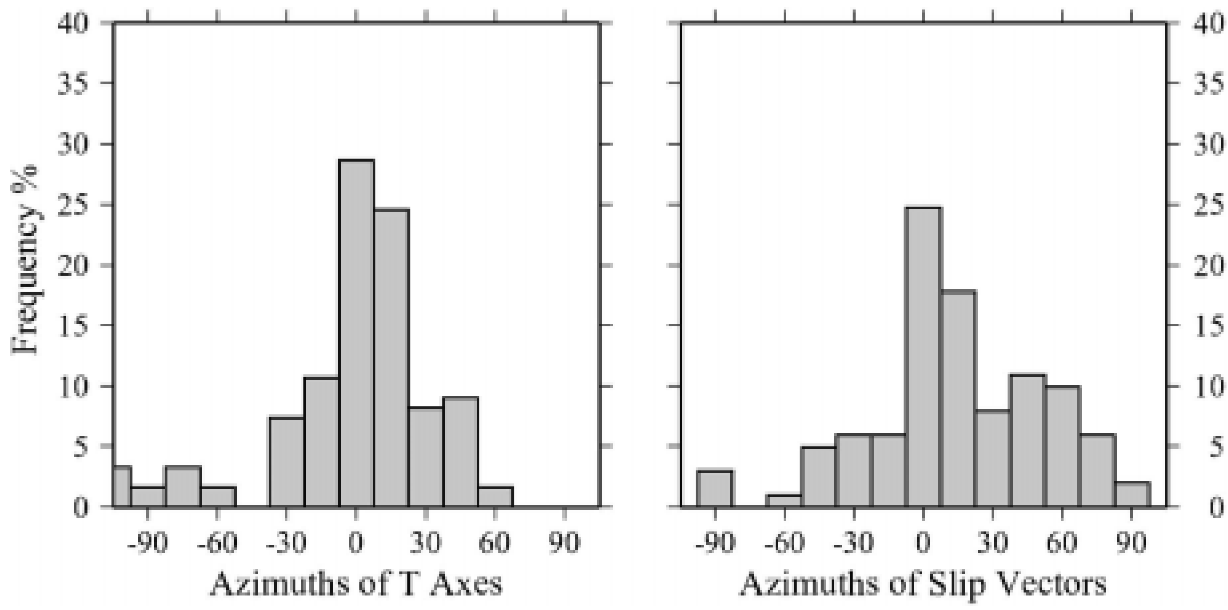

Figure 5. Distributions of the azimuths of slip vectors and of T-axes for the earthquakes shown in Figure 2.

It has similarly been argued (Le Pichon 1982; McKenzie 1972) that the deformation within the Aegean region is being driven by the potential energy contrast between the continental crust of Greece and Turkey and the oceanic crust of the Mediterranean ocean floor. Early geodetic determinations of velocities in Greece (Billiris *et al.* 1991; Davies *et al.* 1997) suggested that the predominant sense of motion is from the relatively elevated interior of the Aegean towards the topographically lowest part (and, presumably, the part lowest in gravitational potential energy) of the Hellenic trench. Other recent interpretations, however, have emphasised the degree to which the velocity vectors can be fit with plate tectonic models (e.g., Le Pichon *et al.* 1995; McClusky *et al.* 2000).

The observations presented in the previous section show that, as Molnar *et al.* (1973) observed in Asia, the principal axes of the moment tensors for the earthquakes in the Aegean region show a simple alignment. Molnar *et al.* (1973) observed that the P-axes (shortening directions) in Asia are aligned with gradients of surface height; the observation in the Aegean region is that the T-axes (extensional directions) are aligned with the strain field determined geodetically. Both the earthquakes and the geodetic strain fields in the Aegean show alignment of their extensional axes towards regions of low potential energy (Figure 4).

In the northern and central Aegean this alignment is roughly north–south, towards the generally low potential energy of the ocean floor south of the subduction zone. In the more southern parts of the region, the orientation of the maximum extension directions swings round to point towards the locally deepest part of the Mediterranean ocean floor; thus in southwestern Greece, the extension is directed towards the deepest part of the West Hellenic trench, whereas in the southeastern Aegean and southern Turkey, the extension is directed towards the deep ocean floor southeast of Rhodos.

It is noteworthy that the Amorgos earthquake (25.9°E, 36.6°N) has a T-axis that agrees very well in orientation with the maximum horizontal extension axis derived from the geodetic measurements of strain of the region. Although the geodetic strain rate of the southern Aegean region is low and velocities there may, therefore, be fit with small residuals to a pole of relative rotation (e.g., Le Pichon *et al.* 1995; McClusky *et al.* 2000), the observation that the principal axis of seismic elongation of the region agrees with the principal axis of geodetic elongation, which in turn is aligned with local gradients of topographic height, suggests that it may not be useful to treat the southern Aegean as a micro-plate. This suggestion has previously been made, on different grounds, by England & Jackson (1989).

From the observations discussed above, I conclude that, as in Asia, the tectonics of Greece, the Aegean Sea, and western Turkey are not dominated by rigid plates, but by the mechanics of a continuous medium responding to contrasts in its gravitational potential energy.

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