On the active tectonics of the Aegean Sea and the surrounding lands

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ABSTRACT

Fault plane solutions for 179 earthquakes, of magnitude M $\geq$ 5.5 and shallow focal depth (h< 60 km), which occurred in the Aegean Sea and surrounding area (34°N- 43°N, 18°E-30°E) during the period 1953-1999, are used to stress some aspects on the active tectonics. These focal mechanisms fall into three main categories: 1) Low-angle thrust and reverse faulting along coastal Albania, western Greece, the convex side of the Hellenic arc (SW of Zante up to NE of Rodos island). This type of faulting is attributed to the collision between the Eurasian and the Adriatic plates and to the northward motion of Africa and the subduction along the Hellenic trench. 2) Normal faulting in the back arc Aegean area that covers the Aegean Sea and parts of the adjacent lands (eastern mainland and northern Greece, western Turkey, southern Bulgaria, southern former Yugoslavia). This kind of faulting is attributed to internal deformation probably caused by gravitational collapse of the expanding area. 3) Strike –slip faulting in a belt that marks the boundary of the Aegean plate with the Eurasian plate. This belt starts from the North Anatolian fault in the east, crosses the northern Aegean Sea, stops abruptly against central Greece before becoming evident again along the Cephalonia - Lefkada transform fault zone and Peloponnese, in the west. Earthquake slip vectors and GPS and SLR velocity vectors are in good agreement and demonstrate that the westward escape of the Anatolian plate, the SW movement of the Aegean plate, and the overthrusting along the Hellenic arc as well as the subduction play a key role in the seismotectonic picture of the area.

1. INTRODUCTION

The Aegean Sea and the surrounding lands, a part of eastern Mediterranean, are among the most seismically active regions (fig. 1) and have the sixth place in the world. The distribution of seismicity in fig.1 shows that the interior of the Aegean and Anatolian plates has sparse seismicity, that is these plates exhibit small internal deformation.

It is well known that the study of fault plane solutions provides a valuable tool towards the understanding of the active tectonics of an area, as they give information on the orientation of the stress field and on the direction of the plate motions. Furthermore, fault plane solutions combined with seismicity studies can be used to determine the seismic part of the total crustal deformation along plate boundaries. Since a long time ago, efforts have been made to study the fault plane solutions of the area, determined by first onsets of teleseismic

P waves (Hodgson and Cock, 1956; Papazachos, 1961; Delibasis, 1968; McKenzie, 1972, 1978; Ritsema, 1974), by first onsets of P waves of local earthquakes (Kiratzi et al., 1987; Hatzfeld et al., 1988, 1996, 1997; Hatzidimitriou et al., 1991) and by waveform modeling of teleseismic body waves (Kiratzi and Langston, 1989, 1991; Kiratzi et al., 1991; Taymaz et al., 1990, 1991; Papadimitriou, 1993; Baker et al., 1997; Louvari, 2000; Louvari et al., 1999, 2000; Louvari and Kiratzi, 2000; Kiratzi and Louvari, 2000).

Over the years a significant number of fault plane solutions for the broader Aegean area has been published, determined either for specific seismotectonic studies or reported by the Harvard and NEIC centers. The rapid increase of digital instrumentation and the deployment of new stations for the global networks have greatly improved the reliability of the published focal mechanisms.

In this paper we present the results of a new database of fault plane solutions for shallow earthquakes ($h<60$ km) in Greece and the adjacent lands, for the period 1953-1999. This database consists of 179 focal mechanisms in total. From these mechanisms 144 have been determined by waveform modeling and the left 35 using first motion polarities. From this database, the focal mechanisms for 65 events have been determined, (Louvari, 2000), using the technique of waveform modeling (McCaffrey et al., 1991). This database is further supported by another database consisting of 1206 focal mechanisms of microearthquakes, determined through the deployment of portable seismographs in Greece during the last 10 years. We are currently developing a database of focal mechanisms of intermediate-depth earthquakes, in order to have a reliable base of fault plane solutions for earthquakes in Greece and the surrounding area.

2. Distribution of focal mechanisms

The focal mechanisms of our database are plotted in fig. 2, as a lower hemisphere equal area projection. The data have been divided into three categories according to the dip of the T and P axes, following Zoback (1992). Red colors represent the focal mechanisms for thrust and reverse faulting, green for normal faulting and black colors represent focal mechanisms for strike-slip faulting. Some hatched focal mechanisms, observed south of Crete island, represent shortening in a E-W direction, which is different from the shortening extensively observed in this area, which has an NE-SW direction. These events, actually, indicating E-W shortening, have focal depths ~40 Km and probably represent internal deformation of the subducting lithorsphere of the African plate (Hatzfeld et al., 1989; Kiratzi and Papazachos, 1995; C. Papazachos, 1999).

Fig. 2 comes to intensify our previous knowledge concerning the active tectonics of the Aegean area (Papazachos et al., 1984; Papazachos et al., 1991, 1992, 1998; Louvari and Kiratzi, 1999; Louvari, 2000). Thus, the major characteristics of the area are:

A. The zones of low-angle thrust and reverse faulting:

a) Along the western coasts of Albania, NW coastal Greece, up to the Ionian Islands, due to the interaction of the Adriatic block and the European plate.

b) Along the Hellenic Arc, south of Zante Island up to Rodos, due to the eastern Mediterranean subduction beneath the Aegean.

B. The zone of normal faulting:

a) Along N-S striking normal faults, running along the Dinarides-Hellenides mountain belt (Papazachos et al., 1984; Armijo et al., 1992).

b) Along ~E-W striking normal faults connected to the back-arc extension.

C. The zone of strike-slip faulting:

a) Along the North Anatolian fault and its continuation into the northern Aegean Sea
b) Along the Lefkada – Cephalonia fault.

Fig. 3 represents a triangle diagram, following Frohlich (1992, 2001), showing the distribution of focal mechanisms in the Aegean area and the surrounding lands. It is observed that all mechanisms fall into the three main categories, that is, thrust, normal and strike-slip faulting. Very few mechanisms deviate from these categories. Fig.4(a) shows the depth distribution of the earthquakes, whose depths were estimated using waveform modeling and thus their depths are more reliable. It is observed that most of the events lie in the range of 6-15 km of the crust and very few events have focal depths deeper than 20 km. Fig. 4b shows the distribution of the earthquakes that have focal depth greater than 40 km. All these events are connected with zones of collision and are mainly distributed along the Hellenic arc and are obviously associated with the zone of subduction (Taymaz et al., 1990, 1991; Kiratzi and Papazachos, 1995).

Kinematic Analysis

Comparison of geodetic velocity vectors with earthquake slip vectors

A number of geodetic studies have been performed in the broader Aegean area during the last years (Billiris et al., 1991; Oral, 1994; Straub, 1996; Straub and Kahle, 1994; Davies et al., 1997; Reilinger et al., 1997; Clarke et al., 1998; Cocard et al., 1999; McClusky et al., 2000). From the comparison of velocity vectors, as derived from geodetic measurements and the slip vectors derived from earthquakes, we may have a picture of the active tectonics of an area.

Fig. 5 shows a comparison between velocity vectors (black arrows) obtained from GPS and SLR measurements in respect to stable Eurasia and earthquake slip vectors (red arrows) as obtained from the database of focal mechanisms. We have plotted only these slip vectors for which we had other means to assume the fault plane. These means are: the distribution of aftershocks of large events, the motion of the dextral strike slip faults along the North Anatolian Fault zone and along the Cephalonia – Lefkada fault, the fact that along the zone of thrusting the low dip angle fault is considered as the fault plane. Thus, fig. 5 indicates that upper crust, at least up to the depth of the seismogenic layer (~15 Km) deforms in the same pattern. The GPS and SLR velocity vectors indicate that the area north of the North Anatolian Fault and northern Greece move slowly and probably belong to stable Eurasia. On the contrary there is a clear increase of the Anatolian plate velocity towards the west, and of course we can also visualize the rapid motion of the Aegean plate towards the Hellenic trench, with velocities that reach a value of 30 ± 1 mm/yr (McClusky et al., 2000).

Of special interest is the fact that the area extending from the Gulf of Amvrakikos, in western Greece, to the Ionian Islands and western Peloponnese is moving in a different manner in respect to the adjacent regions. This variation in the magnitude of the motion is probably connected to the forces developed by the plate motions. Thus, the SW motion of southern Aegean, as well as the motion of the Adriatic block in the west, enhance shear compressive forces in this region, resulting in a faster motion towards SW (Cocard et al., 1999).

A synthesis of plate motions

Fig. 6 gives a picture of the contemporary ideas concerning the motion of the plates that are involved in the kinematics of the Aegean area. The Eurasian, African and Arabian are the major plates that affect active tectonics as well as the motion of smaller plates, namely the Anatolian plate, the Aegean plate and the Adriatic block. The Arabian plate moves in a NNW direction relative to Eurasia at a rate of about 18-25 mm/yr, averaged over about 3 Myr (DeMets et al., 1990). The motion of Arabia is considered as the cause of the westward escape of the Anatolian plate relative to Eurasia, towards the Aegean. This escape is facilitated by the presence of two major strike-slip faults: the North Anatolian and East Anatolian faults (Sengör et al., 1985; Papazachos et al., 1998; McClusky et al., 2000). Also, Anatolia is rotating counter-clockwise, relative to Eurasia, about an Euler pole located north of the Sinai Peninsula (31.1°N, 33.4°E), which predicts a velocity of 24 mm/yr at the North Anatolian Fault (Oral et al., 1995; C. Papazachos, 1999).

The Aegean plate seems to be quite well defined. Its NW boundary is defined by the Cephalonia-Lefkada Transform Fault (CTF), while its eastern boundary is defined by the zone of extensional tectonics in western Turkey (Papazachos et al., 1998; C Papazachos, 1999; McClusky et al., 2000). The north boundary is defined by the belt of intense earthquake activity connected to the North Anatolian fault, its continuation into the northern Aegean Sea, a broad zone that passes through Thessaly and ends up at the Cephalonia – Lefkada fault.

The Aegean plate (McKenzie, 1970, 1972, 1978) is moving fast towards the SW. This motion is facilitated by the presence of the subduction at the Hellenic trench. The convergence between the Eurasian and African plates is taking place in a N-S direction along the Hellenic Trench at a rate of 10 mm/yr, at 30°N, 31°E, (Chase, 1978; Minster and Jordan, 1978; DeMets et al., 1990). The leading edge of the African plate is subducting at a higher rate than the rate of convergence between Africa and Eurasia, which implies that the trench is retreating southwards relative to Eurasia (Jackson and McKenzie, 1988a,b). Recent tomographic work (Papazachos and Nolet, 1997) shows that the plate interaction along the Hellenic trench is of ocean - continent character especially in southeastern Ionian (area of Cythera), since remnants of oceanic crust still exist beneath the Hellenic trench.

In the west, along coastal Albania and former Yugoslavia, active continental shortening and crustal thickening occur, caused by the collision of the region with the Adriatic and Apulian platforms. It is now thought, that it is this collision that resists the westward motion of Anatolian and forces the Aegean Sea to the SW, where it can easily override the Mediterranean oceanic crust along the Hellenic Trench (Jackson, 1994). The Adriatic lithospheric microplate is considered as an extension of the African lithospheric plate (a wedge) in the area between Italy and the former Yugoslavia - Albania - west central Greece. It has been suggested that this microplate is rotating counter-clockwise (McKenzie, 1972; Ritsema, 1974; Anderson and Jackson, 1987). This rotation results in a convergence of this plate with the Eurasian plate along the eastern Adriatic and north Ionian coastal area and contributes to the generation of earthquakes with thrust faulting.

The distribution of shallow earthquakes in the Aegean Sea and the surrounding land show that earthquakes do not occur only along the boundaries of the lithospheric plates described above but also in the adjoining regions of these plates. For instance, the Aegean plate indicates little internal deformation at southern Aegean, however there is a considerable amount of deformation taken up by faulting in northern Greece, eastern Albania, southern former Yugoslavia, and southern Bulgaria, where this deformation is generally of extensional character.

It is true that we can make the assumption that provided we average over length scales comparable to the lithosphere thickness the deformation of the upper crust approximates the distributed flow in the rest of the lithosphere beneath it. It is also well known that a fundamental question in continental tectonics concerns the velocity field that describes the deformation of the lithosphere at large length scales and how faulting in the upper crust accommodates this velocity field. There is not known today the relation between the velocity field and faulting and the information we can get from that about the interaction between the upper crust and the creeping lithosphere beneath it. People tend to believe that the structural anisotropy of the upper crust influences the direction in which faulting forms or reactivates. Moreover, the overall velocity field may adjust with time to keep these faults active as they and the blocks they bound rotate. We believe that even though the deformation in the Aegean could be represented by a continuous velocity field one cannot neglect the effect of the motion of the plates in this area.

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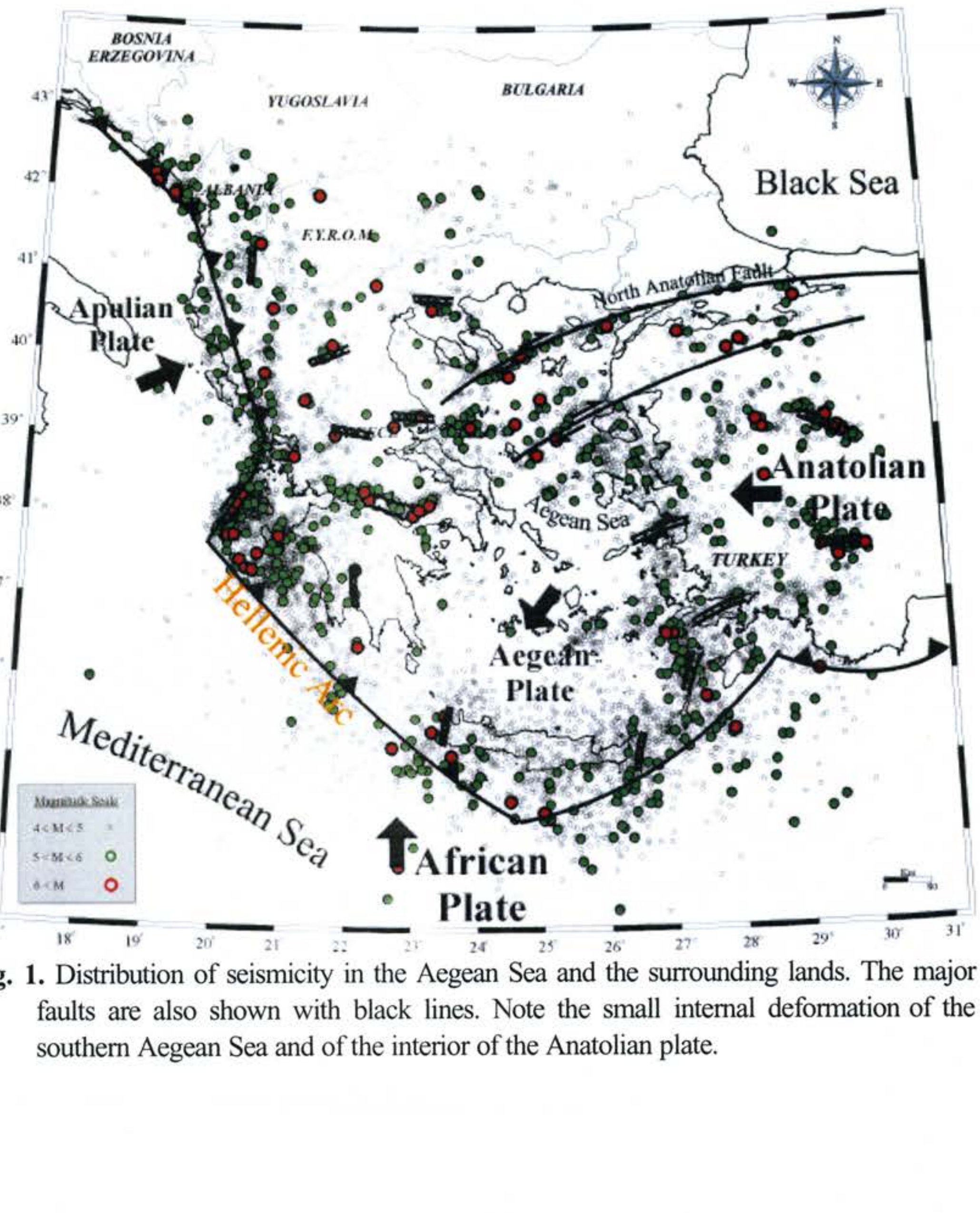

Fig. 1. Distribution of seismicity in the Aegean Sea and the surrounding lands. The major faults are also shown with black lines. Note the small internal deformation of the southern Aegean Sea and of the interior of the Anatolian plate.

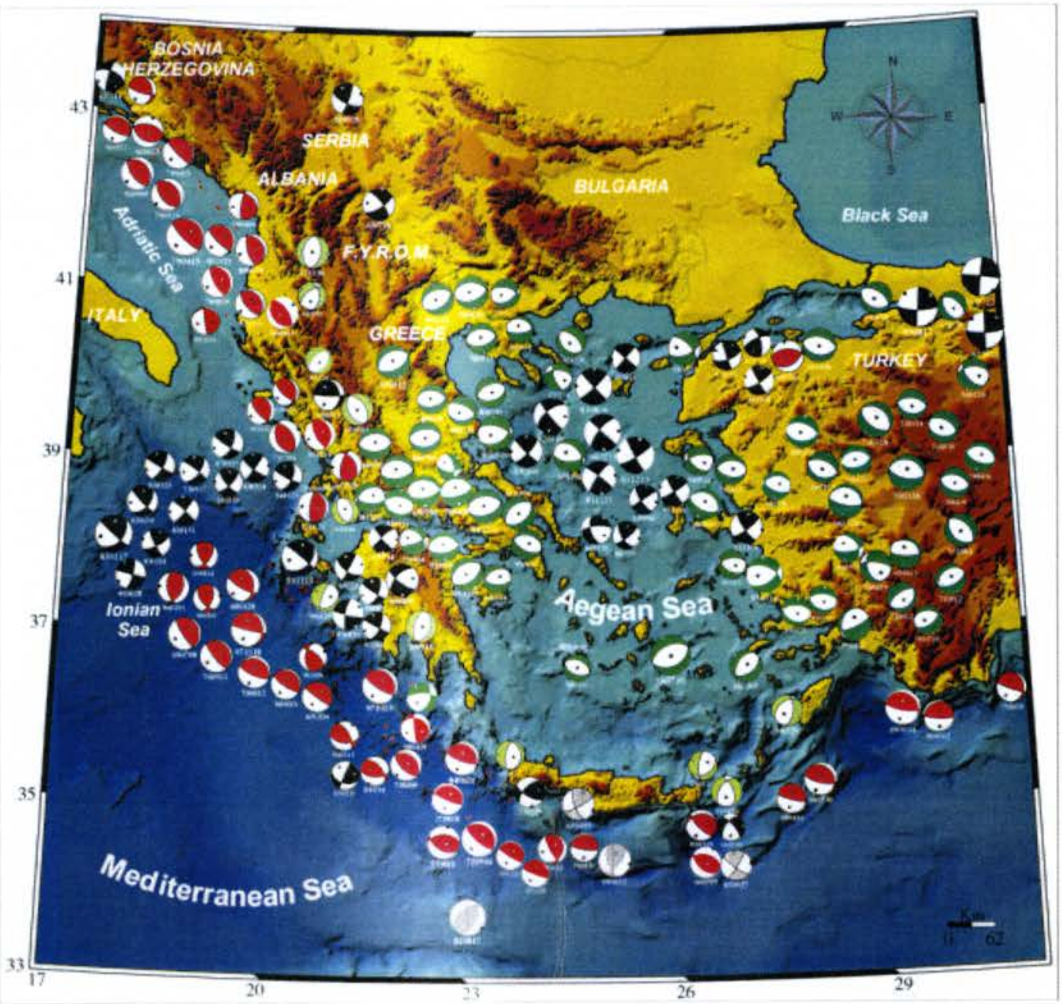

Fig. 2. Fault plane solutions of shallow (h<60 km) earthquakes of the period 1953-1999, with Mw $\geq$ 5.0. A lower hemisphere equal area projection is used with the color quadrants denoting compression and the white ones denoting dilatation. The date of each event is also shown in the figure. Note the distribution of thrust and reverse faulting (red beach-balls) along the coastal Albania and western Greece as well as along the Hellenic trench. The back-arc Aegean area is characterized by tensional faulting (green beach-balls). Strike-slip faulting (black beach-balls) is connected to the North Anatolian fault and its bifurcated strands into the Aegean as well as to the Cephalonia – Lefkada transform zone in the west.

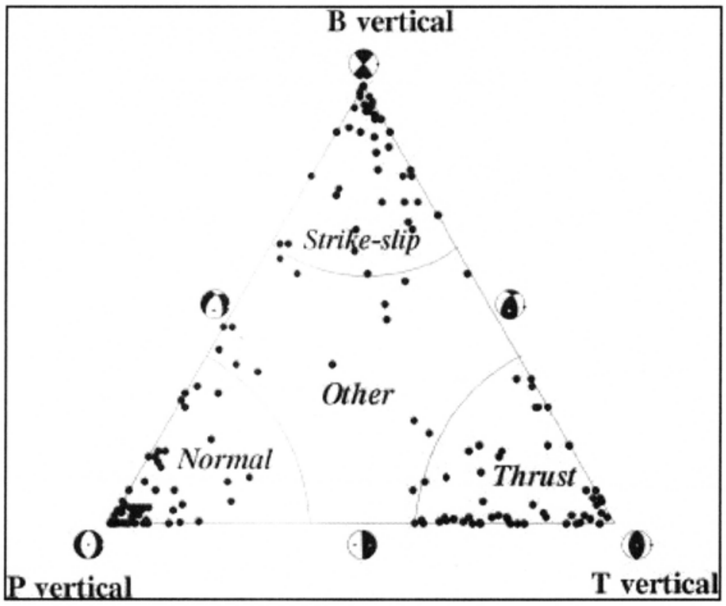

Fig. 3. Triangle diagram for displaying the distribution of the focal mechanisms (following Frohlich, 1992, 2001) that consist our database for earthquakes in Greece and the surrounding lands. Mechanisms with vertical P, T and B axes plot at the vertices of the triangle. Most of the focal mechanisms in Greece fall into the three main categories and very few deviate from those.

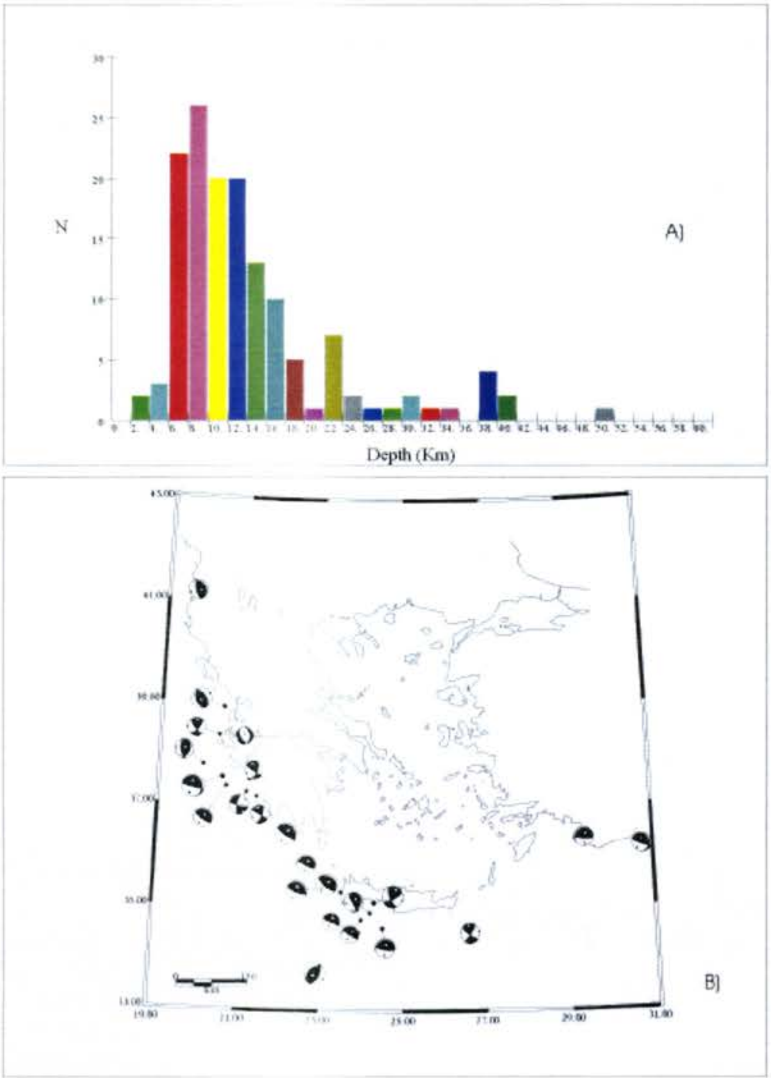

Fig. 4. a) Distribution of focal depths, which have been estimated by waveform modeling and thus are more accurate. Note that very few events have depths greater than 20 km. The events that have focal depths >40 km are all distributed along the zones of compression as is shown in (b).

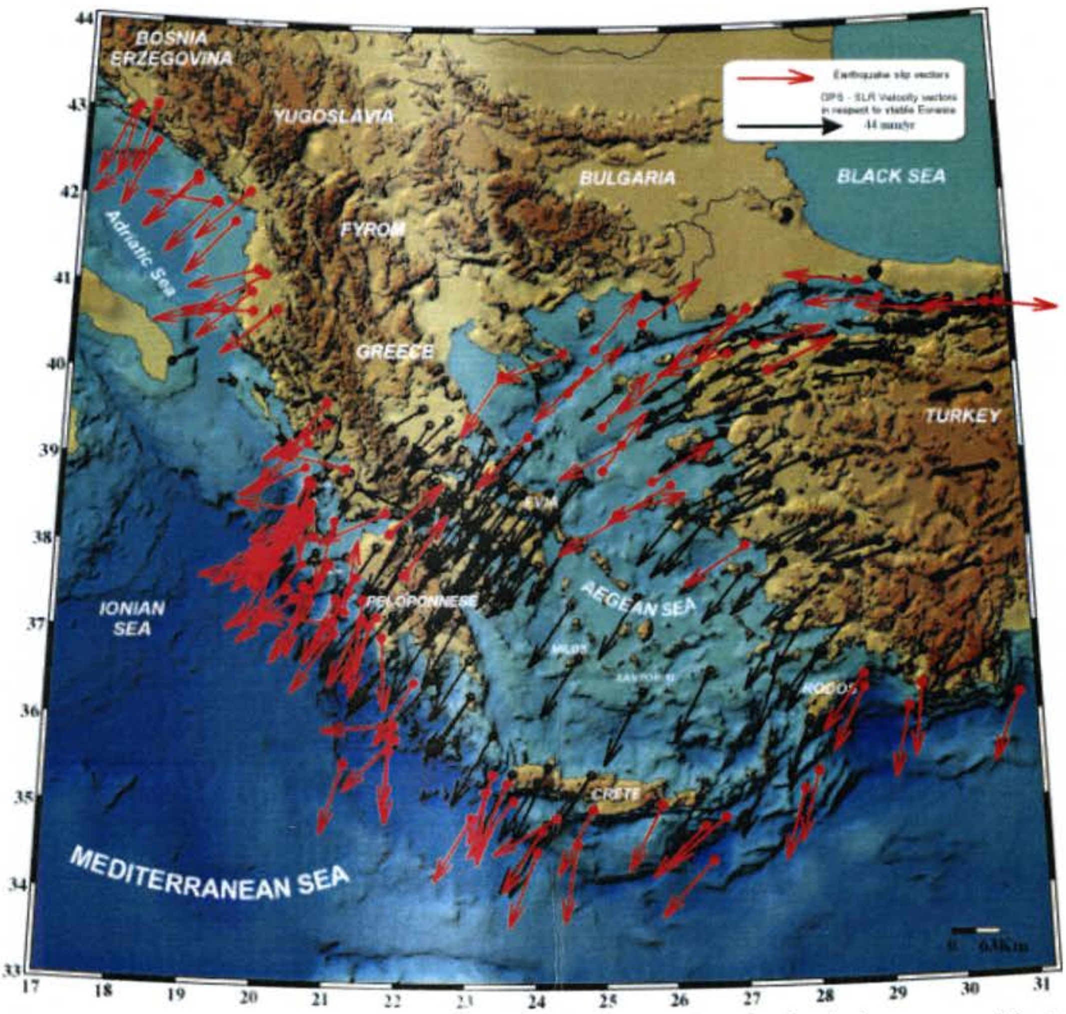

Fig. 5. Comparison of earthquake slip vectors (red arrows) and of velocity vectors (black arrows) obtained from GPS and SLR measurements (data from Oral, 1994; Reilinger et al., 1997; Clarke et al., 1998; Cocard et al., 1999; McClusky et al., 2000). Earthquake slip vectors represent movement of the hanging wall relative to the foot wall.

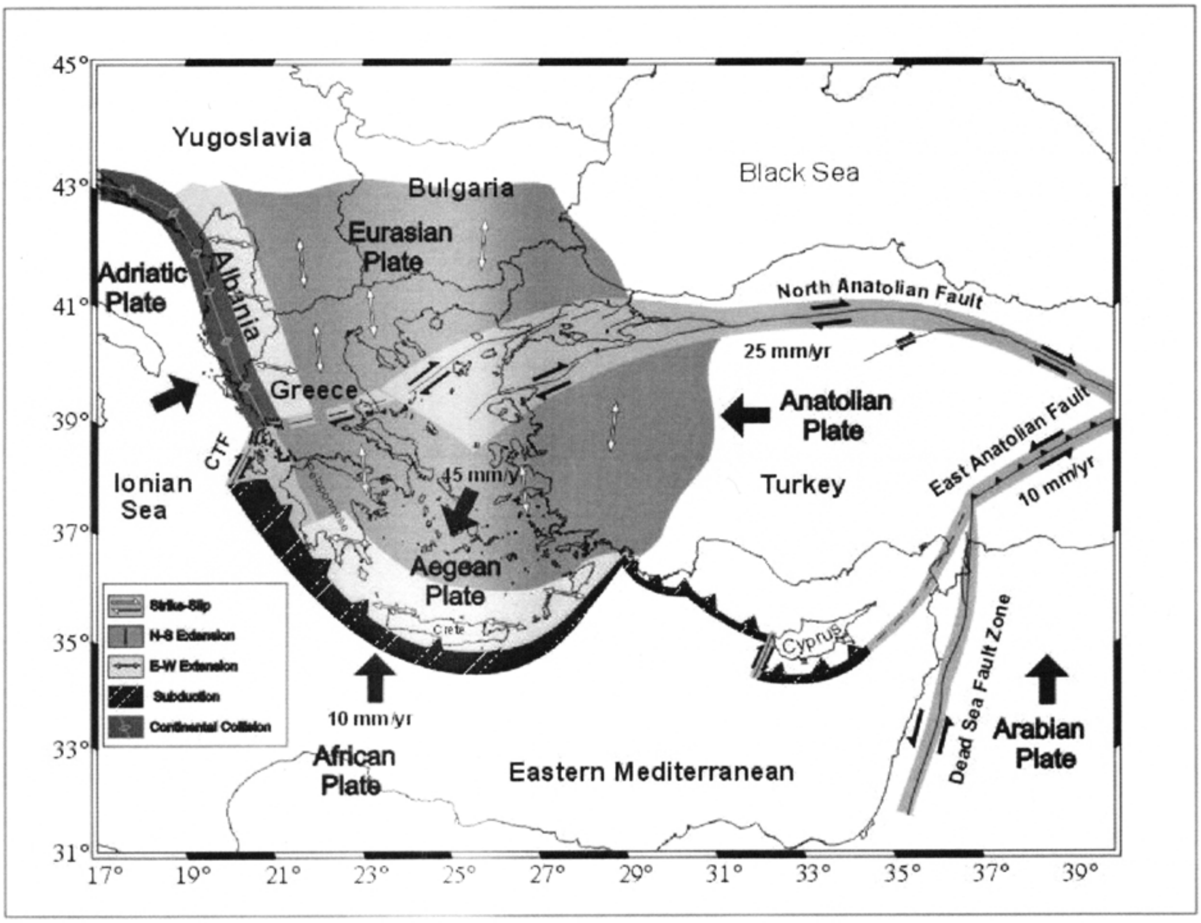

Fig. 6 Simplified map of the Aegean Sea and the surrounding area showing the large plates involved in the active tectonics. Black arrows indicate the motion of the plates relative to Eurasia. The white small arrows indicate the direction of the internal deformation (extension) in the broader Aegean area (from Papazachos et al., 1998).