

DISTRIBUTED EARTHQUAKE FOCAL MECHANISMS IN THE AEGEAN SEA

Kiratzí A.¹, Benetatos C.¹, and Roumelioti Z.^{1,2}

¹ Department of Geophysics, Aristotle University of Thessaloniki, 54124, Greece,
Kiratzí@geo.auth.gr, chmpenet@geo.auth.gr, zroum@geo.auth.gr

² National Observatory of Athens, Geodynamic Institute, Athens

Abstract

Nearly 2,000 earthquake focal mechanisms in the Aegean Sea and the surroundings for the period 1912- 2006, for $1.5 \leq M \leq 7.5$, and depths from 0 to 170 km, indicate a uniform distribution and smooth variation in orientation over wide regions, even for the very small magnitude earthquakes. ~ 60% of the focal mechanisms show normal faulting, that mainly strikes ~E-W. However, a zone of N-S normal faulting runs the backbone of Albanides-Hellenides. Low-angle thrust and reverse faulting is confined in western Greece (Adria-Eurasia convergence) and along the Hellenic trench (Africa-Eurasia). In the central Aegean Sea the effect of the propagating tip of the North Anatolian Fault into the Aegean Sea is pronounced and strike-slip motions are widely distributed. Shearing does not cross central Greece. Strike-slip motions reappear in the Cephalonia-Lefkada Transform Fault zone and in western Peloponnese, which shows very complex tectonics, with different types of faulting being oriented favourably and operating under the present stress-field. Moreover, in western Peloponnese the sense of the observed shearing is not yet clear, whether it is dextral or sinistral, and this lack of data has significant implications for the orientation of the earthquake slip vectors compared to the GPS obtained velocity vectors.

Key words: seismotectonics, Greece, deformation, focal mechanisms.

Περίληψη

Περίπου 2000 μηχανισμοί γένεσης σεισμών που εκδηλώθηκαν στο Αιγαίο και τη γύρω περιοχή κατά το χρονικό διάστημα 1912-2006, με μεγέθη $1.5 < M < 7.5$ και εστιακά βάθη μεταξύ 0 και 170 km, εμφανίζουν ομοιόμορφη κατανομή και ομαλές διακυμάνσεις προσανατολισμού μέσα σε περιοχές μεγάλης έκτασης. Το συμπέρασμα αυτό προκύπτει τόσο από τους μεγάλους, όσο και από τους μικρότερους σε μέγεθος σεισμούς. Ένα ποσοστό ~60% των διαθέσιμων μηχανισμών γένεσης δείχνουν κανονική διάρρηξη, με επικρατέστερο προσανατολισμό ~Α-Δ. Ωστόσο, κατά μήκος της «ραχοκοκαλιάς» των Αλβανίδων-Ελληνίδων παρατηρείται κανονική διάρρηξη κατά τη διεύθυνση Β-Ν. Διαρρήξεις σε μικρής γωνίας κλίσης ανάστροφα ρήγματα παρατηρούνται συγκεντρωμένες στη δυτική Ελλάδα (όριο σύγκλισης Αδριατικής-Ευρασίας) και κατά μήκος του ελληνικού τόξου (όριο σύγκλισης Αφρικής-Ευρασίας). Στο κεντρικό Αιγαίο, η συνέχεια του δυτικού άκρου του ρήματος της Βόρειας Ανατολίας κάνει έκδηλη τη δυναμική του με τη μορφή ρηγμάτων οριζόντιας μετατόπισης. Οι διατμητικές αυτές κινήσεις δε συνεχίζουν στην κεντρική ηπειρωτική Ελλάδα, αλλά επανεμφανίζονται στο

ρήγμα μετασχηματισμού Κεφαλλονιάς-Λευκάδας και στη δυτική Πελοπόννησο. Στη δυτική Πελοπόννησο το τεκτονικό καθεστώς εμφανίζεται ιδιαίτερα πολύπλοκο, με διάφορους τύπους ρηγμάτων να εμφανίζουν προσανατολισμό που ευνοεί τη διάρρηξη τους κάτω από το σημερινό πεδίο τάσεων. Στην περιοχή αυτή τα σεισμολογικά δεδομένα δεν είναι ακόμα επαρκή για τον ασφαλή προσδιορισμό του χαρακτήρα, αριστερόστροφου ή δεξιόστροφου, των οριζόντιας μετατόπισης κινήσεων και αυτό έχει αντίκτυπο στη σύγκριση του προσανατολισμού των σεισμολογικά προσδιορισμένων διανυσμάτων ολίσθησης με τα διανύσματα ταχυτήτων που προκύπτουν από την επεξεργασία γεωδαιτικών δεδομένων.

Λέξεις κλειδιά: σεισμοτεκτονική, μηχανισμοί γένεσης, Αιγαίο Πέλαγος.

1. Introduction

The Aegean Sea and the surrounding lands, a region lying in the crossroads of major and smaller plates (Fig. 1), exhibits interesting geodynamic features (McKenzie 1972, 1978, Jackson and McKenzie 1988, Dewey and Sengör 1979, Jackson 1994, Papazachos and Kiratzi 1996, Papazachos *et al.* 1998, McClusky *et al.* 2000 among many others). Plate motion models indicate that the Arabian plate is moving northwards relative to Eurasia at a rate of $\sim 18\text{-}25$ mm/yr, averaged over ~ 3 Myr. The African plate is also moving northwards relative to Eurasia at a rate of less than 10 mm/yr. Its leading edge is being subducted along the Hellenic Trench. As the rate of subduction is higher than the relative motion of Africa relative to Eurasia, it requires a southward movement of the arc relative to Eurasia. The Anatolian block is moving south-westwards and this motion is facilitated by the presence of the subduction where the Aegean plate can easily override the subducting edge of the African plate. The presence of the North and East Anatolian strike-slip faults further facilitate the westward escape of the Anatolian plate.

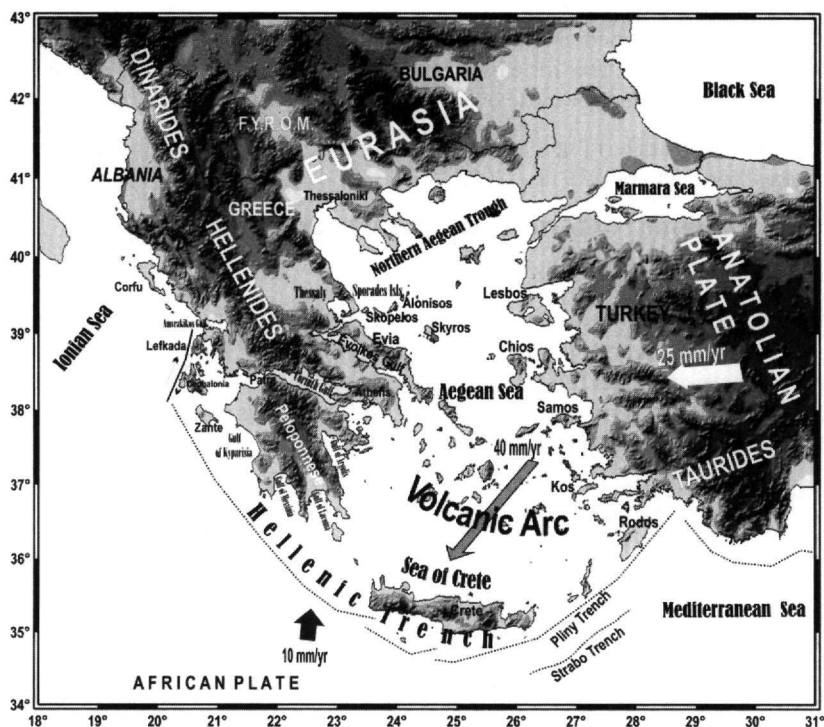


Figure 1 - Location map of the Aegean Sea and the surrounding lands. Arrows indicate the motion (McClusky *et al.* 2000) of the plates relative to Eurasia

Earthquake focal mechanisms include significant information for the seismotectonic picture of any region, the distribution of slip vectors compared to other vector fields, the present day stress-field, to mention just a few.

Over the years we have compiled a data base of focal mechanisms (e.g. Kiratzi and Louvari 2003 and references therein), which is continuously updated with newly determined events using continuously higher-quality digital data from broad band sensors, recently (2006) installed at the seismological network operated by the Department of Geophysics of the Aristotle University of Thessaloniki.

In this work we analyse the structure of the focal mechanism database, we classify them into fault types, we examine the spatial distribution of focal mechanisms and we discuss certain aspects of the seismotectonics of the region.

2. Structure of the earthquake focal mechanisms database

2.1. Focal mechanisms determined by first motion polarities

The database covers the region 19-31° E, 32-42°N and includes: **a)** published focal mechanisms of microearthquakes recorded by temporary networks which were installed on land and were in operation for limited time periods, mainly in the framework of EC funded projects. Epicentres, focal depths, and magnitudes for these events are those listed in the relevant publications. Usually the magnitudes of these microearthquakes are calibrated against duration magnitudes; **b)** published focal mechanisms of strong shocks ($M_w > 5.5$) determined using first motions read on long-period instruments, mainly on WWSSN 15-100s instruments, with a peak response at around 15s period, and for which the polarities were published together with the solutions themselves. These data are especially for earthquakes before 1970's. The epicenters, focal depths and magnitudes for these events are those published in the catalogue of Papazachos *et al.* (2006). This catalogue contains either relocated epicenters for earthquakes in Greece, or those listed in the ISC and NEIS bulletins. The magnitudes listed for these events are M_w following Papazachos *et al.* (1997).

In total, focal mechanisms determined using first motion polarities are included in the database for 1,422 earthquakes, for the period 1912 – 2003.

2.2. Focal mechanisms determined by waveform modelling

The database includes:

a) published focal mechanisms determined by widely used methods of waveform inversion, basically based on a ray theory approach (e.g. McCaffrey and Nábělek 1987, McCaffrey *et al.* 1991) applied to teleseismic data (distances in the range of 30° to 90°) or moment tensor inversion techniques applied to waveforms from broadband sensors at regional distances (for example the technique of Dreger and Helmberger 1990, 1991, 1993).

b) the above dataset has been enriched with focal mechanisms available from Harvard University determined using the normal mode approach, commonly referred to as “centroid moment tensor” or CMT analysis. More specifically, we searched the Harvard catalogue from 1976 up to April 06 and if a solution was not included in the database already, from a published separate work, then the Harvard solution, if contained more than 70 % double couple component, was added in the database. Additionally, few solutions reported from ETH (<http://www.seismo.ethz.ch/>) or from MEDNET (<http://mednet.rm.ingv.it/events/>), especially for regions where the cover of focal mechanisms was not sufficient, were also included in the database. We must emphasize here, that the epicentres for the source parameters from Harvard and ETH are those reported in Papazachos *et al.* (2006) with the previous commentary. The source parameters of the earthquakes published in the literature are likely to be more reliable than those available in the routinely determined CMT or other bulletins, thus these solutions were preferentially entered into the database.

In total, the source parameters for 572 earthquakes, of the period 1959 – 2006, determined by waveform modelling techniques are included in the database, for which all magnitudes are M_w 's and the focal depths are the most reliable within the database. The database is complete for $M_w > 5.5$ for the period 1976 – 2005.

Obviously, as in the database are included focal mechanisms determined by different techniques the database itself is not homogenous. For instance, teleseismic body wave inversion schemes and the CMT technique have significant differences. In the body wave approach we assume a double couple source and, for shallow sources, we typically look at a data window of ~ 20 to 40s. Usually, after removing the instrument we convolve the waveforms with the response of the long period WWSSN 15-100 instruments (with a peak response at ~ 15 s). This processing retains sufficient low frequency for most of the sources of moderate magnitude events to look simple, and at the same time there is substantial high frequency in the waveforms to be sensitive to the separations of the depth phases, (i.e. P and pP and P and sP separations), which control the source depth. Thus, the source depth is well resolved for both shallow ($h < 40$ km) and deeper events. It is an advantage of the method that for the distances used, the inversion is insensitive to the structure near the source and the receiver.

The CMT method solves for the six independent components of the Centroid Moment Tensor and even though no volume change is usually assumed, which means that the trace of the moment tensor equals zero, it does not require the source to be a double couple. Moreover, the lowpass filter applied to the waveforms at ~ 0.022 Hz (~ 45 s) for Harvard solutions and the longer time windows used, compared to the time windows used in the classic body wave analysis, results in inability to resolve depths for shallow events. This is why many reported depths from Harvard are fixed at 15 km or sometimes 33 km to indicate a shallow source, whereas any Harvard solutions that include broad band stations have better resolution in depth.

3. Classification of Earthquake Focal Mechanisms

Based on the criteria listed in Table 1 we have classified the focal mechanisms of the database into four categories and we plot their spatial distribution in separate figures. The software RAKE (Louvari and Kiratzi 1997) was used to organize the database and perform the queries. It is noticeable the uniform organization of focal mechanisms in very wide regions, with few anomalies, which most of the times are related to small magnitude earthquakes (small faults) or mechanisms related to aftershock sequences. The deviation of the focal mechanisms of the small magnitude events from the nearby mechanisms of the stronger events is not significant in the Aegean Sea region, indicating the organization of the strain field at long wavelengths in conformity with the origin of the large scale driving forces on the edges of the deforming regions or even within the deforming regions themselves (England and McKenzie 1982).

3.1. Normal Faulting and normal faulting combined with shear motion

Approximately 60 % of the database focal mechanisms indicate normal faulting (Fig. 2-top), sometimes combined with considerable strike-slip component, along mainly E-W trending planes, while the N-S trending normal faulting (Fig. 2-bottom), representing ~ 25 % of the total mechanisms exhibiting normal faulting, is distributed along the Albanides and Hellenides Mountain range (roughly along the Gavrovo-Tripolitza and Pindos nappe geological zones), and along the accretion prism in southern Aegean Sea. Nodal plane dips (both planes considered) are in the range of $30^\circ - 65^\circ$ with the average to be $\sim 50^\circ$. Evidence from the strongest and best studied normal faulting events (e.g. Volos 1980, Thessaloniki 1978, Kozani 1995, Aigio 1995 to mention a few) did not provide strong evidence for listric geometry at shallow depths (< 5 km) simply because of the lack of seismicity at these shallow depths. On the contrary, judging from the distribution of aftershocks, in cross-strike profiles these major normal faults appeared approximately planar.

Table 1 - Classification of the focal mechanisms, included in the database, based on the plunge of P, T and B axes (following Zoback 1992)

Plunge of axes		Faulting type
P axis	T axis	
$pl \geq 52^{\circ}$	$pl \leq 35^{\circ}$	Normal faulting [NF]
$40^{\circ} \leq pl \leq 52^{\circ}$	$pl < 20^{\circ}$	Normal faulting combined with considerable strike – slip component [NS]
$pl \leq 35^{\circ}$	$pl \geq 52^{\circ}$	Thrust faulting [TF]
$pl \leq 20^{\circ}$	$40^{\circ} \leq pl < 52^{\circ}$	Thrust faulting combined with considerable strike – slip component [TS]
$pl < 40^{\circ}$ (and plunge of B axis $\geq 45^{\circ}$)	$pl < 40^{\circ}$	Strike – slip faulting [SS]
All P, T and B axes plunge in the range $25^{\circ} < pl < 45^{\circ}$ OR Both P and T axes plunge in the range $40^{\circ} < pl < 50^{\circ}$		Unclassified type of faulting [U]

3.2. Pure thrust - Reverse Faulting and/or combined with shear motion

The focal mechanisms that show thrusting (low-angle thrust, dipping $\leq 35^{\circ}$, or reverse faulting, dipping $> 35^{\circ}$), sometimes combined with considerable strike-slip motions, comprise ~ 14 % of the total mechanisms included in the database (Fig. 3). Thrust faulting dominates the foreland and hinterland flanks of collision tectonics in Albania, where the collision of Adria – Eurasia occurs without subduction process, whereas along the Hellenic Trench system thrusting is attributed to the collision of Africa – Eurasia with a well developed subduction zone. Local areas of thrusting shown in Figure 3 (e.g. south of North Anatolian Fault, event of 3 March 1969) could well be attributed to contractional irregularities on strike-slip faults (Yeats *et al.* 1997).

3.3. Strike – Slip Faulting

Strike-slip motions in Greece (~ 26 % of the total focal mechanisms included in the database) are distributed in broad regions (Fig. 4). In northern Aegean Sea the shearing is considered a sign of the continuation of the right-lateral shear of the North Anatolian Fault Zone.

Most of the focal mechanisms in Northern Aegean Sea, of the strongest and best studied events, are clearly connected with right lateral motion, except in the case of Skyros 2001 earthquake (inset A in fig. 4) where an activation of a NW-SE fault with sinistral strike-slip motion was detected (Benetatos *et al.* 2002, Ganas *et al.* 2005 and references therein). Moreover, the focal mechanisms in Alonisos and Skopelos islands, could be also attributed to the operation of NW-SE structures with sinistral strike-slip component (Koukouvelas and Aydin 2002, Kiratzi 2002, Nyst and Thatcher 2004). The absence of any shearing in central Greece is evident (Fig. 4). Not even small magnitude events were detected that would indicate that the shear crosses central Greece, where the E-W normal faulting is clearly operating. In the Ionian Islands the strike-slip motions are well connected with the Cephalonia-Lefkada Transform Fault Zone (Fig. 5).

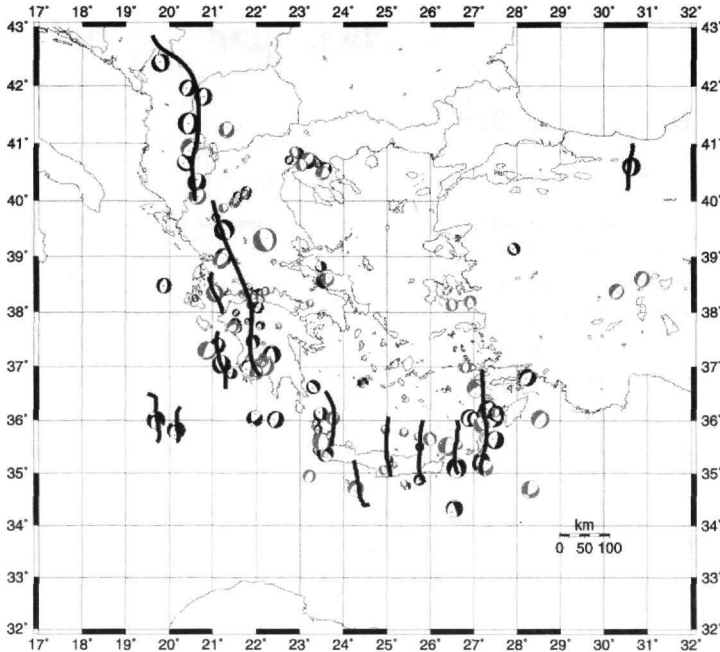
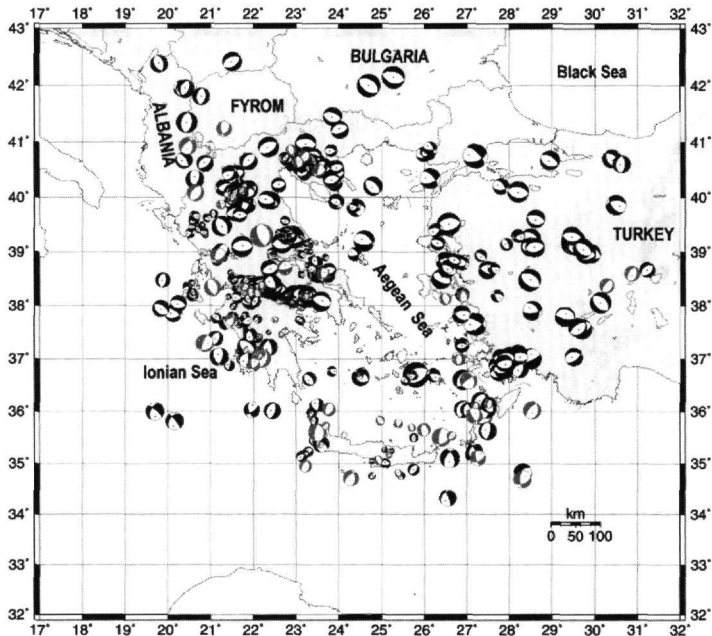


Figure 2 - top: Normal faulting focal mechanisms (either pure normal or combined with strike-slip component). The size of focal spheres scales with magnitude; Bottom: Normal faulting with N-S strike only (sketched as straight lines), to show the regions of E-W extension which mainly follow the mountain range Albanides – Hellenides and the sedimentary arc. In all cases, black focal spheres are for shallow sources ($h \leq 40$ km) and light- grey shaded mechanisms are for deeper sources ($h > 40$ km).

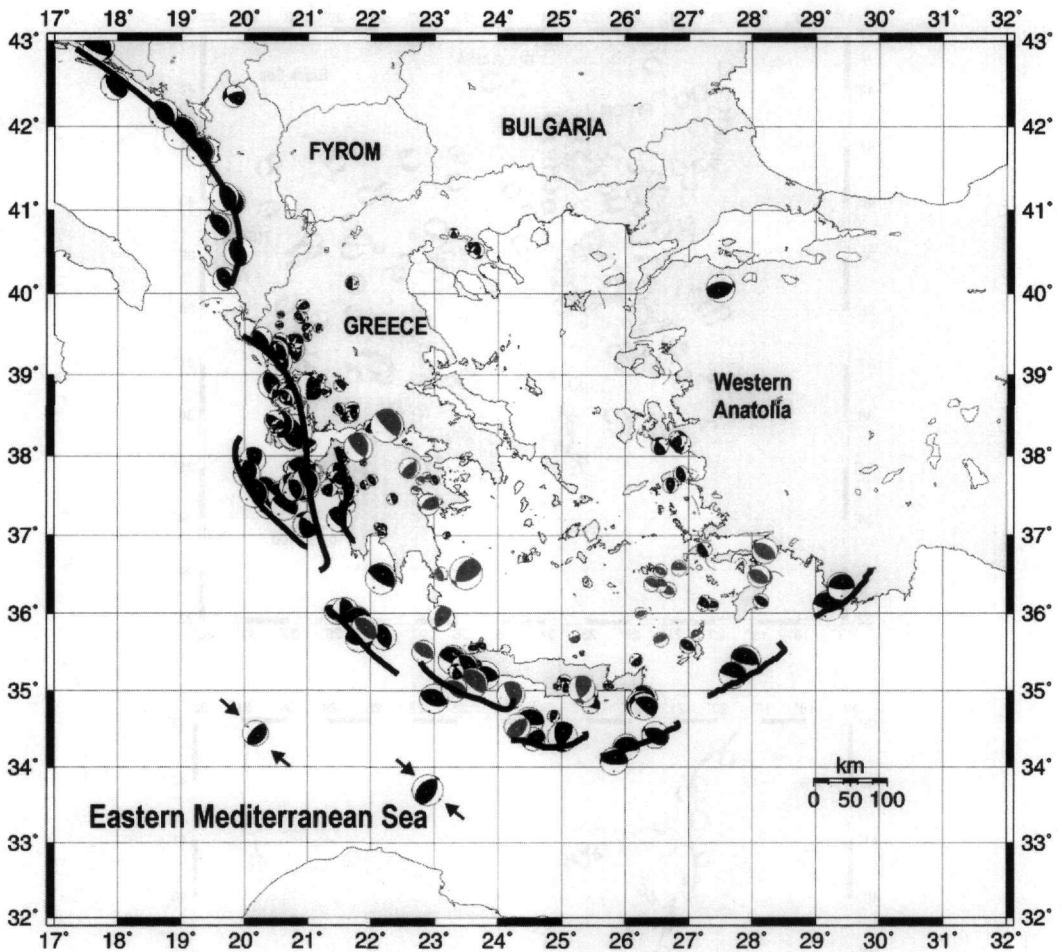


Figure 3 - Focal mechanisms classified as thrust or reverse faulting (either pure thrusting or combined with strike-slip component). Size and shading of focal spheres as in Fig. 2. The straight lines are free sketched to delineate the region of thrusting. Note the zone passing from western Greece through the inner part of Ionian Islands and in western Peloponnese. Also note that the crust in Eastern Mediterranean is compressed along a NW-SE direction

What is also noticeable is the shear motions observed along the western coast of Peloponnese especially in the Gulf of Kyparissia (Fig. 5). The 1988 Killini, 1993 Patras, 1993 Pirgos and 2002 Vartholomio earthquakes were moderate in size, however the distribution of their aftershocks shows evidence of the operation of sinistral strike-slip motions in this region. In general, western Peloponnese shows complex tectonics, due to its proximity to different structures, the Cephalonia-Lefkada Transform to the west and the Hellenic trench to the SW. Many structures are favourably oriented to the present stress field, the presence of evaporates in the region and their effect in the seismotectonic picture is not also clearly known. In general strike-slip faulting in Greece seems to develop in parallel or conjugate sets, accommodating crustal deformation over broad areas, often with significant rotations of crustal blocks about vertical axes (Jackson 1994).

3.4. Unclassified focal mechanisms

A few focal mechanisms of the database (Fig. 6) do not fall into any of the categories of Table 1 and they are mostly distributed in the southern part of the Aegean Sea. They indicate dip slip faulting, with very steep or very shallow nodal planes.

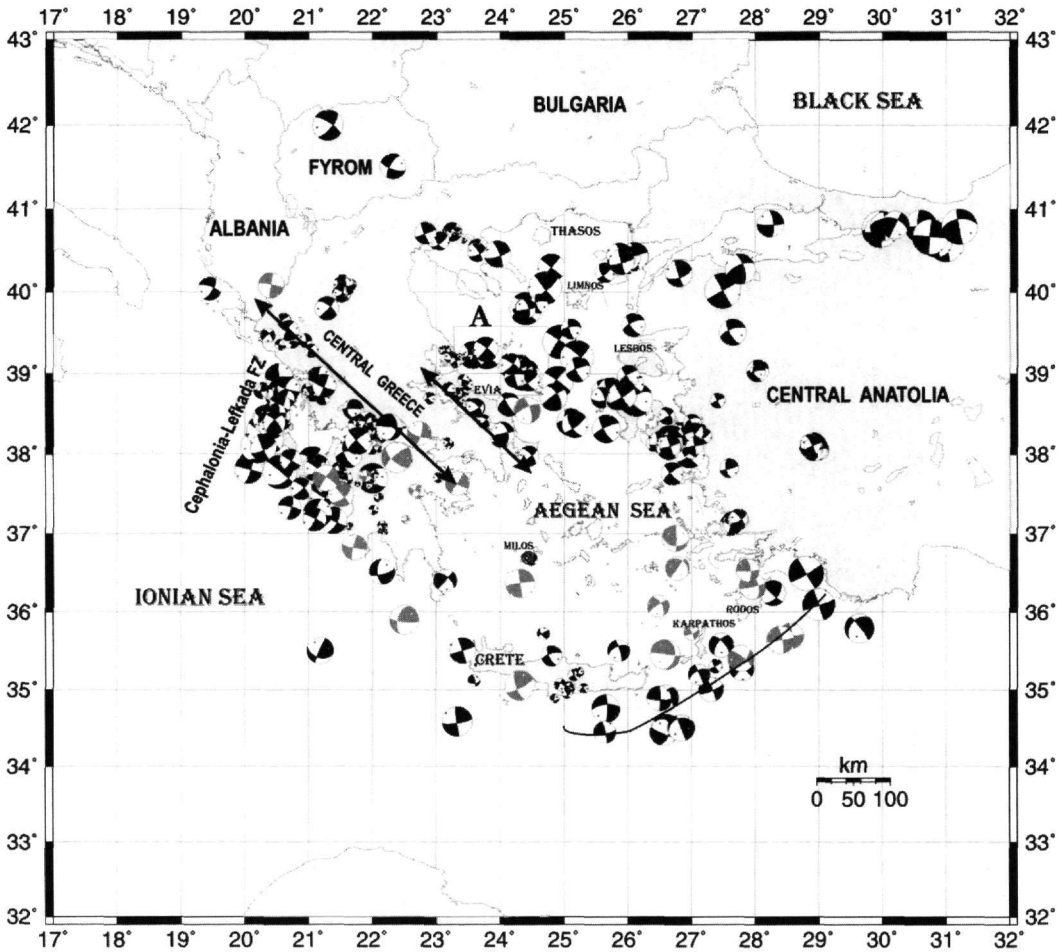


Figure 4 - Strike-slip motions in the Aegean Sea and surrounding land areas. The black double-headed arrows indicate the edges of shear motion penetration from the east, and the re-appearance of shear motions in the west. Note the absence of shearing in central Greece (not a single mechanism observed). Size and shading of focal spheres as in Fig. 2

4. Thickness of the seismogenic layer

Using better determined Moho profiles (Papazachos and Nolet 1997) for the Aegean Sea and the better constrained focal depths of the earthquake mechanisms included in the database, we can confirm that most of the seismicity is confined within the crust (Fig. 7) and especially within the upper crust. There is no substantial evidence for significant seismicity in the mantle, except of course the region of the subduction which is also well defined by the best determined focal depths.

The maximum depth of earthquakes in the crust (Fig. 7), which defines the thickness of the seismogenic layer, is of the order of 10 to 20 km in the Aegean Sea, and this gives a scale for the quantification of the dimensions of active structures in the region. Earthquakes in the broader Aegean Sea capable to rupture the entire thickness of the seismogenic layer should be considered as large events, or alternatively are produced from large faults. Those events with ruptures confined within the seismogenic layer are considered as moderate-size events, or are produced from small faults.

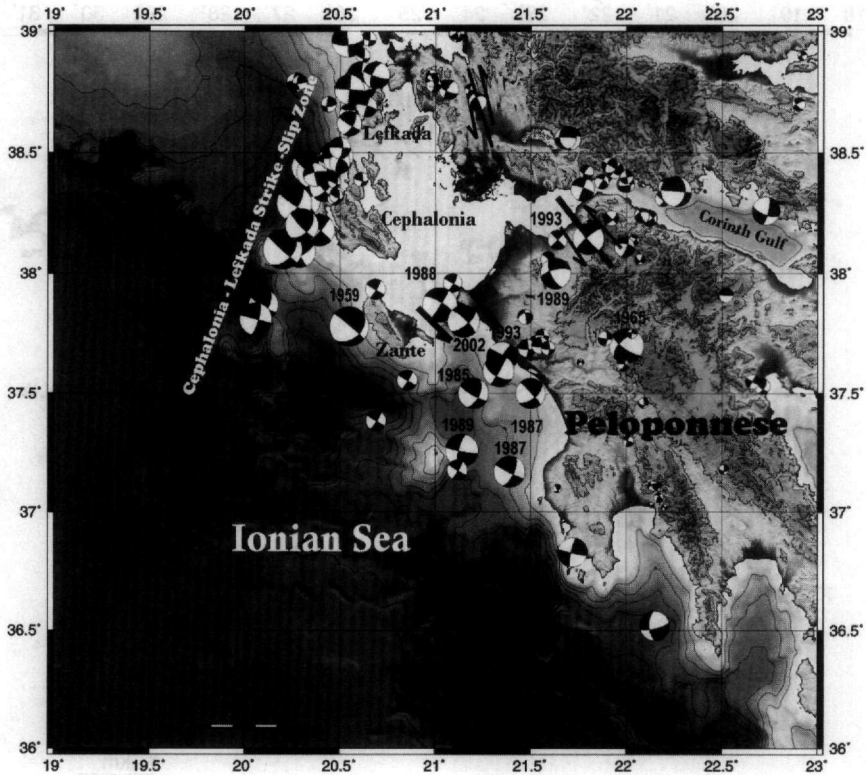


Figure 5 - Distribution of strike-slip motions in SW Greece, with emphasis in western Peloponnese and Gulf of Kyparissia. Size and shading of focal spheres as in Fig. 2. This region, not well covered by the GPS networks in Greece, indicates complex deformation not well explained by the, at least at present, available kinematic models of Aegean tectonics (not discussed here)

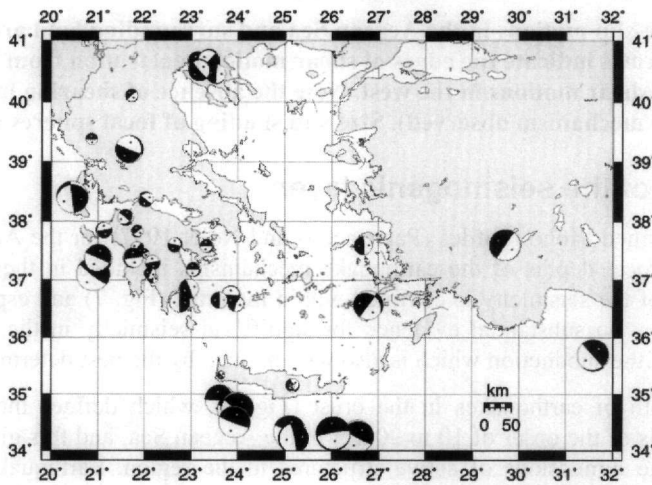


Figure 6 - Unclassified focal mechanisms

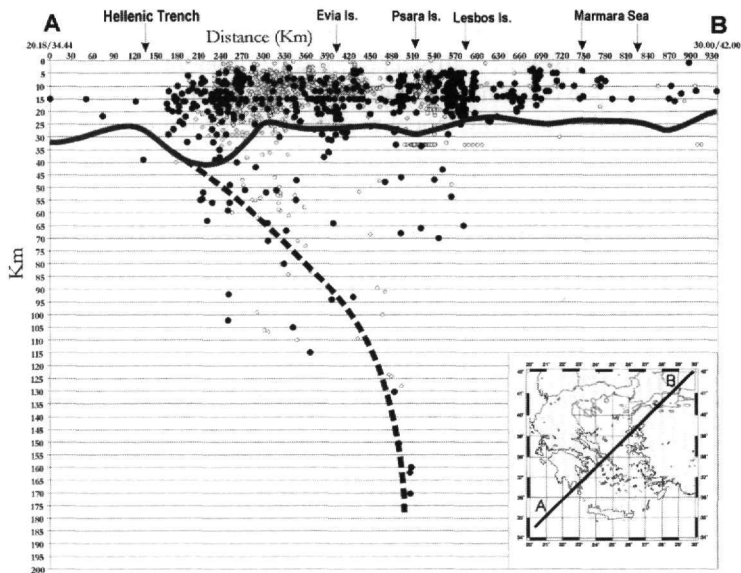


Figure 7 - Cross-section along the line A-B (see inset) to see the distribution of the best determined focal depths (black dots from waveform modelling), light grey for mechanisms determined from first motion polarities, thus these data are only added for comparison, in terms of the variation of Moho (straight line) within the section. Note the confinement of seismicity within the crust, especially to the upper 15 to 20 km, whereas the deeper events are well confined in the subduction zone, (dashed line)

5. Conclusions

Earthquake focal mechanisms in Greece and the surrounding lands indicate spatial uniformity and reflect the distributed continental deformation in the region. A database comprising 1,994 focal mechanisms for the years 1912 -2006 has been compiled, which includes mechanism from different fault scales (from microearthquakes to strong earthquakes). The best determined focal depths confirm that the thickness of the seismogenic layer in the Aegean Sea and the surroundings is about 15 to 20 km, and all the seismicity is well confined within the crust, with little seismicity in the mantle, mainly related to the subduction in southern Aegean Sea. The deepest event for which a focal mechanism is available is at 173 km depth, and is located beneath the island of Psara, west of Lesbos Island.

Deformation in continental Greece is mainly taken up by normal faulting, with an E-W strike, while the operation of a normal faulting zone, with N-S strikes of faults, aligned along the mountain belts of Albania – Greece and along the accretion prism in southern Aegean is also well confined. Strike –slip motions are wide spread in the northern Aegean Sea sometimes combined with normal component or reverse component. The right lateral shearing is diffuse across a wide NE-SW trending band connecting the Marmara Sea region to Corinth Gulf. Shearing is not detected, at least from the available focal mechanisms, to cross central Greece; however, it reappears in western coastal Greece, western Peloponnese and Ionian Islands. One important aspect in Northern Aegean Sea is the partitioning of strike-slip and dip-slip motions (normal faulting) with the strike-slip faulting prevailing from the two.

Although in the Ionian Islands the dextral sense of motion is well documented, in western Peloponnese and farther north in Epirus, the sense of motion is not well documented. There are indications though, from the distribution of aftershocks, the distribution of seismicity, and topography that the sense of shearing is sinistral. Actually, the proximity of strike-slip motions with different orientations of the slip vectors in western Peloponnese requires special attention in

the future, in terms of what is predicted from plate motion models and what is observed from the GPS obtained velocity vectors (Fig. 8). In general, the deformation of the Aegean Sea and the surroundings is attributed to the combination of gravitational potential energy differences and plate interaction, probably in equal terms. Any model proposed for the region should fit the distribution of focal mechanisms for the strong events (Fig. 8) and should also be compatible with what is expected from the geodetic measurements (Nyst and Thatcher 2004).

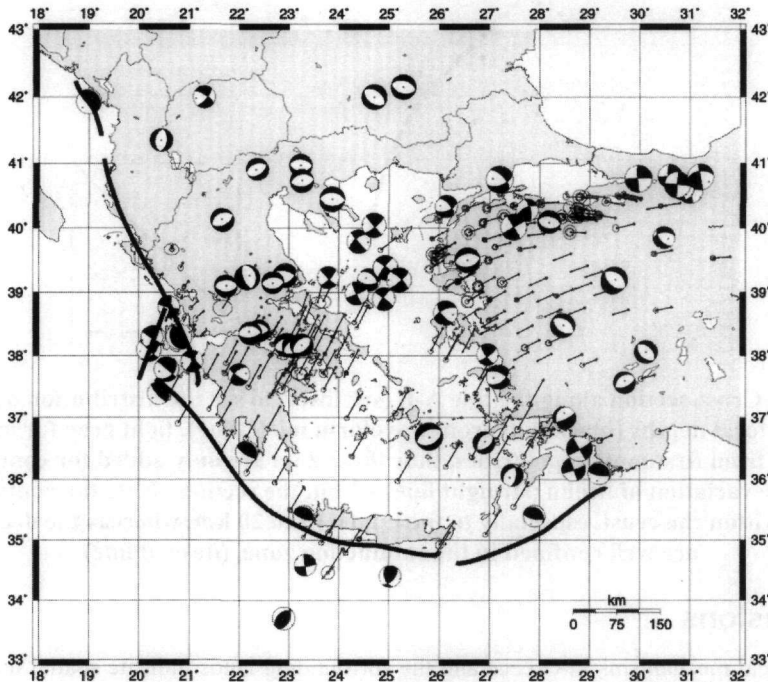


Figure 8 - Observed GPS obtained velocity vectors, relative to Eurasia (data as in Nyst and Thatcher, 2004) and focal mechanisms for strong ($M_w \geq 6.0$) and shallow ($h < 40$ km) earthquakes. Any model for the region should be in accordance with these observations

6. Acknowledgments

This work was supported in part by the Ministry of National Education and Religious Affairs (Project Pythagoras II and Project INTERREG IIIA, Greece – Fyrom) and by the General Secretariat of Research and Technology (Ministry of Development). Most of the figures were done using the GMT software (Wessel and Smith, 1995).

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