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MICROEARTHQUAKE SEISMICITY AND FAULT PLANE SOLUTIONS IN NORTHWESTERN GREECE

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ABSTRACT

The analysis of microearthquake data obtained during an experiment conducted in northwestern Greece in 1989, reveals a rather complex pattern for the area. The reliably located seismicity is crustal and diffusely distributed. However, high seismicity level zones are observed, separated by low activity, or inactive areas. The computed fault plane solutions show a complicated pattern of deformation. The westernmore external zone is characterized mainly by reverse and strike-slip faulting, while the easternmore zone by normal faulting. Moreover, a superposition of normal and reverse mechanisms, is observed across the major part of the area.

The results of the microearthquakes' analysis, supplemented with previous body wave modeling studies and CMT solutions for large earthquakes, are used to determine the stress field distribution. Additionally, the calculated slip vector and results of geodesy measurements, are considered to constrain a kinematic model, in order to interpret the overall pattern of the area.

INTRODUCTION

The region of northeast Mediterranean is characterized by intense deformation. The kinematics of the deformation is controlled by three factors: the westward motion of Turkey relative to Europe in the east, the continental collision between northwestern Greece and the Apoulian platform in the west and the active Hellenic subduction in the south. The convergence rate between the two plates is about 1cm/yr (Argus et al., 1989), while being significantly larger along the Hellenic trench (7-10cm/yr) (Le Pichon & Angelier, 1979; Jackson & McKenzie, 1988; Jackson, 1994), where subduction of the African lithosphere beneath the Aegean occurs. The intermediate depth stress field is dominated by compressive mechanisms along the trench, from western Peloponnesus to Rhodes, while the upper crust deformation is characterized by extension within the Aegean (Taymaz et al., 1991; Taymaz, 1990; Jackson, 1994; Jackson & McKenzie, 1988; Jackson et al., 1982).

Epirus, Akarnania and the Ionian islands lie near the transition between the Hellenic subduction occurring south of Kefallinia island and a region where continents collide in northern Greece (McKenzie, 1972). Between the two regions is situated the important Lixourion dextral strike-slip fault (Cushing, 1985; Sorel, 1989). Three compressive phases have been reported in northwestern Greece: near the Middle Miocene, around the Lower Pliocene and during the Middle Pleistocene, the total amount of shortening being of the order of several hundreds kilometers (IGRS-IFP, 1966). The fact of whether it is about discontinuous episodes or continuous deformation is still a subject of debate (Jackson et al., 1982; Underhill, 1989). Furthermore, paleomagnetic data show a total of 50° clockwise rotation from Middle Miocene until Plio-Pleistocene (Kissel et al., 1985).

Active reverse faulting is observed in the Ionian islands and within the westernmost mainland of Epirus and Akarnania (Cushing, 1985; Sorel, 1989; Underhill, 1989; Doutsos & Frydas, 1987), while extensional tectonics is observed in a more internal zone in Epirus (Waters, 1993), Akarnania (Sorel, 1989; King et al., 1993; Underhill, 1989) and in the Gulf of Patras (Ferentinos et al., 1985).

The source parameters of large earthquakes occurred in the area show mainly reverse faulting with an intense dextral horizontal shear west of Lefkada and Kefallinia islands (Anderson & Jackson, 1987; Papadimitriou, 1988; CMT-Harvard).

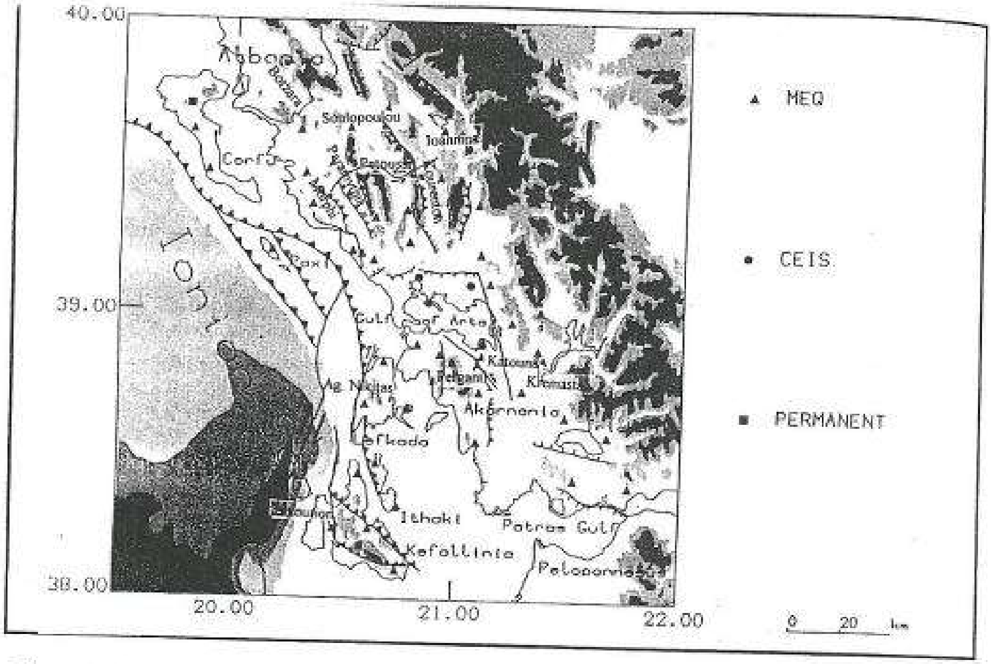


Figure 1. 1989 Seismological network, toponyms and observed faults across the area, discussed in the text.

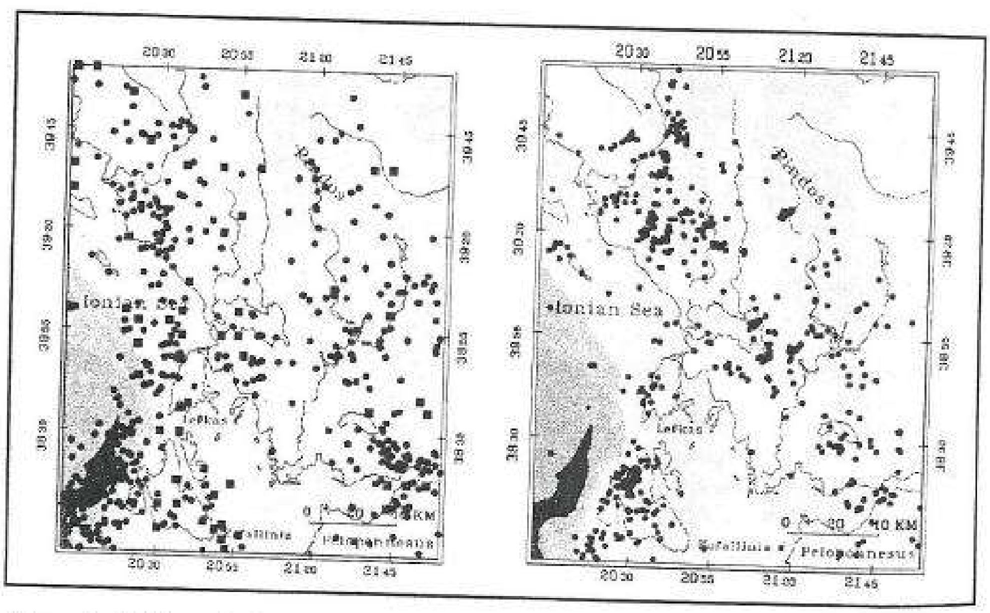


Figure 2a. Background seismicity in northwestern Greece. Squares represent historical data until 1962. Circles denote ISC locations during 1963-1994, M>4

Figure 2b. 1989, microearthquake seismicity, rms<.3, erx<4km

DATA

In 1989, for a period of two months (July-August), a network of 54 one component (1hz) MEQ-800 Sprengnether instruments was installed in Epirus, Akarnania and the Ionian islands from Kefallinia to Corfu, covering a region of about 200x120 km (fig. 1). The spacing between stations was about 15 km. During the experiment, about 1000 events were recorded, from which 656 were located with HYPO71 (Lee & Lahr, 1975), using a Vp/Vs ratio of 1.82 and a calculated velocity structure. The magnitude range for these events is 0.9-4.2. By applying quality criteria we classified 490 earthquakes having location uncertainty less than 8 km and 277 less than 4 km in both horizontal and vertical component.

120 fault plane solutions were computed using P-waves' first motion polarities, from which, for 51 the two nodal planes are constrained better than 20° (quality 1), for 50 the one nodal plane is constrained better than 20° (quality 2) and 19 indicating only the type of deformation (quality 3).

The short duration of the experiment as well as the dimensions of rupture caused by microearthquakes (of the order of a few hundred meters), limit the significance of the small scale revealed deformation. A larger in space and time sample should be taken into account in order to obtain a regional pattern. Thus, the historical seismicity prior to 1963, the ISC catalogues locations (1964-1994, M>4), as well as the source parameters computed for large earthquakes by body waves inversion methods (Anderson & Jackson, 1987; Papadimitriou, 1988; CMT) and the seismic sequence of the May 1993 Parga earthquake (Kassaras et al., 1994) are considered to complete a reliable data set, used in this study.

DISTRIBUTION OF EPICENTERS

The depth distribution above 35 km, of the most reliably located microearhquakes, demonstrates the crustal character of the deformation across northwestern Greece. There is no evidence for active lithospheric subduction beneath Epirus, Akarnania or the Ionian islands north of Kefallinia. This result supports the aspect that the northern boundary of the active subduction lies south of Kefallinia, around Zakinthos island (Hatzfeld et al., 1990; Papadimitriou et al., 1994).

Concerning the spatial distribution of epicenters, comparing the microeathquake locations (figure 2b) and the location of larger events (figure 2a), we obtain a similar pattern, effect confirming a continuous deformation in the area. Concentration of epicenters is seen along the continental shelf, the activity bounded by the 1000 isobath contour for the large earthquakes around Kefallinia and Lefkada islands. Concerning the microearthquakes, the concentration is constrained in a more internal position, along the western shores of the two islands. There is a shift of the order of about 10 km between the large and small events' locations at the specific area. This fact could probably be due to a systematic dislocation of the events included in the ISC catalogues, or the larger earthquakes occur along a zone located western of the one defined by the microearthquakes.

The eastern boundary for the seismic activity is determined by the Pindos mountain chain. High activity is observed in Epirus along the fold and thrust belt of Morphi - Paramythia - Kourenton - Botzara, beneath the subsiding Soulopoulou basin (Waters, 1993), at the eastern coast of Amvrakikos Gulf, around Kremasta dam, Trichonis lake and Patras Gulf. The maritime area north of Lefkada and the block south of Lefkada bound by the eastern coasts of Kefallinia-Lefkada in the east and the Katouna fault in the west, exhibits an aseismic character. In addition, the important Petoussi fault does not reveal an active character in all its length, concerning the microseismicity.

The accurately located microseismicity is distributed in clusters, in the vicinity of active faults observed inland (Waters, 1993; IGRS-IFP, 1966; King et al., 1993; Cushing, 1985; Sorel, 1989). However, no direct association of the hypocenters with any of these features could be performed, except for the Lixourion - Lefkas dextral strike-slip fault (Kassaras et al., 1993; 1994).

STRESS FIELD DISTRIBUTION

In figure 3, quality 1 and 2 fault plane solutions of the 1989 experiment microearthquakes are plotted.

In northern Epirus, one cluster is located west of the Ioannina basin and east of the rapidly subsiding Soulopoulou offset (King et al., 1993), between two anticline zones directing NNW-SSE, bounded by reverse faults (IGRS-IFP, 1966), inferred to be active (Waters, 1993). No fault plane solutions were available for this cluster. West of this zone, a cluster distributed in depth between 5-8 km, reveals normal faulting with the T-axes trending approximately N-S, while a strike-slip component is present. One focal mechanism computed beneath the Ioannina basin, indicates also normal faulting in the same direction.

The Petoussi fault, a major scale left-lateral strike-slip fault, does not appear to be active in all its length, as the only evidence associated with its characteristics, is a single focal mechanism indicating left-lateral strike-slip faulting. This is in agreement with field observations, about the active character of the fault along only some of its segments (Sorel, 1989; Waters, 1993).

Southernmore, the activity is concentrated along the thrust and fold belt of Morphi-Paramythia, where the observed faults are dipping east (IGRS-IFP, 1966). Most of the mechanisms show reverse faulting in NNW-SSE direction, the P-axis trending NE, while some of them reveal normal or strike-slip faulting. The P-axis of these mechanisms is also trending NE, indicating a homogeneous stress field which probably causes deformation along preexisting structures, generating a complex shear pattern. Buried structures trending NE-SW, transverse to the observed ones, are seen in the surface magnetic map of the area and particularly in the 2nd derivative (K.Dimitropoulos, personal communication).

East of Paramythia the pattern is similar, with reverse and significant strike-slip faulting, the P-axes trending NE. Another cluster southern, is located deeper and is characterized by dip-slip normal or reverse focal mechanisms with one shallow dipping plane towards the north. The same pattern was observed during two previous microearthquake campaigns (King et al., 1983; Kiratzi et al., 1987). Above these deeper foci, the northern cluster characterized by normal faulting, is located with a vertical distribution (fig. 4).

The source parameters of large earthquakes (Anderson & Jackson, 1987; CMT), indicate reverse faulting (fig. 6), the P-axes trending NE, in agreement with the P-axes of the small earthquakes. The May-June, 1993 earthquake sequence of Parga (fig. 5), reveals reverse faulting in NNW-SSE direction, the P-axes trending NE (Kassaras et al., 1994).

The fault plane solutions of microeartquakes located along the western coast of Lefkada, indicate a uniform pattern of dextral strike-slip faulting in NNE-SSW direction, with the P-axes trending NE. The depth distribution of these events is shallower than 20 km. This activity could be related to the strike-slip fault of Agios Nikitas observed west of Lefkada (Cushing, 1985; Underhill, 1989). Westernmore, in a zone where the bathymetry changes direction, four events located deeper than 20 km present also strike-slip faulting, but with the P-axes trending SE. This is probably an evidence of change in the stress field orientation, occurring in depth.

Around Kefallinia, the fault plane solutions of microeartquakes exhibit a rather confuse pattern, indicating reverse, strike-slip or normal types of faulting, with the majority of P-axes trending NE. Although only a few focal mechanisms have been accurately constrained (quality 1) due to the poor azimuthal coverage of the epicenters by the network, the data evident that deformation occurring there, is a complexity of several active tectonic features. This fact could be interpreted by taking in account the location of the area within a zone characterized by dextral horizontal shear along the Lixourion-Lefkas fault system, compressive field along several active reverse faults observed inland (Sorel, 1989) and the conjunction with the active subduction occurring southern. The shear complexity of the area may affect and reactivate previous normal faults also seen in the field (Sorel, 1989; Underhill, 1989).

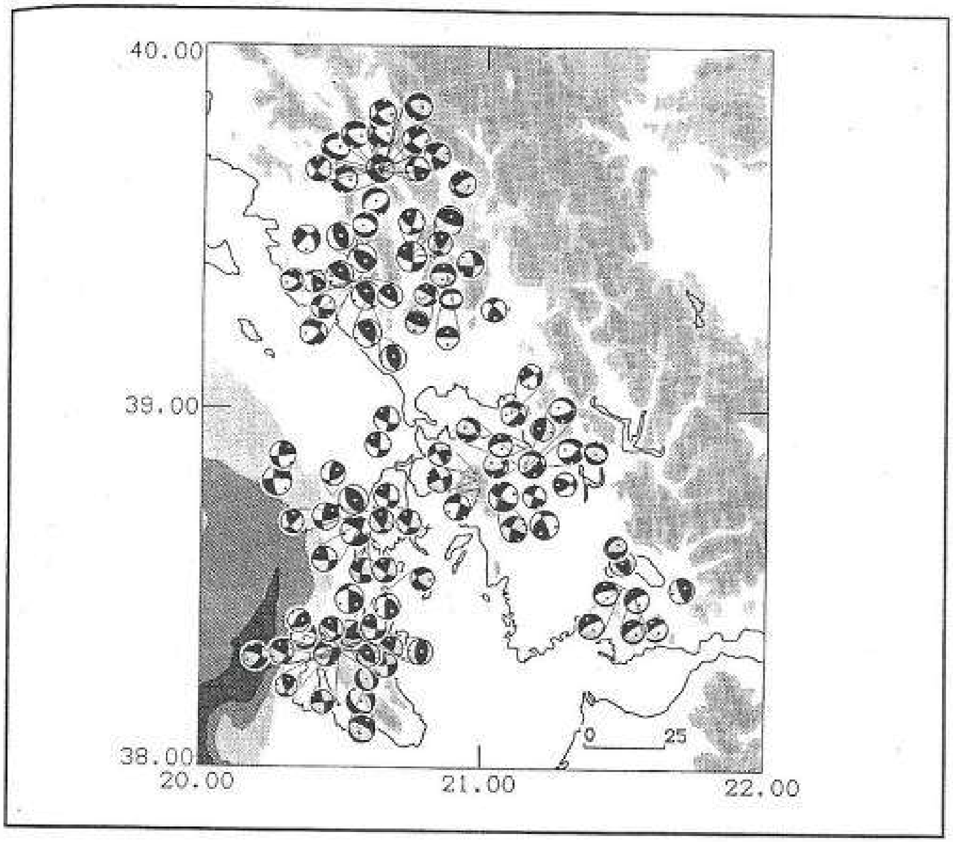


Figure 3. 1989, quality 1 and 2 (gray filling) fault plane solutions.

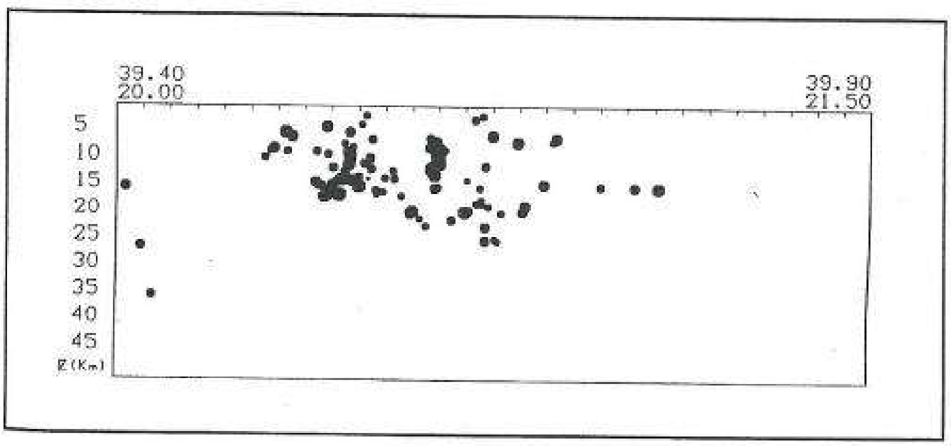
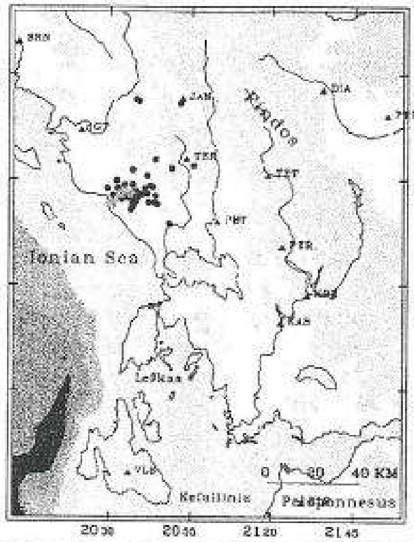


Figure 4. 1989, cross section across Epirus in SW-NE direction, rms<.3, erx<4km.



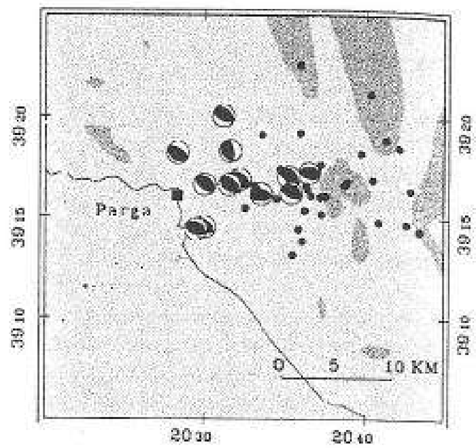


Figure 5a. The 1993 earthquake sequence of Parga and permanent network across the area.

Figure 5b. Parga 1993 sequence, epicenters and fault plane solutions.

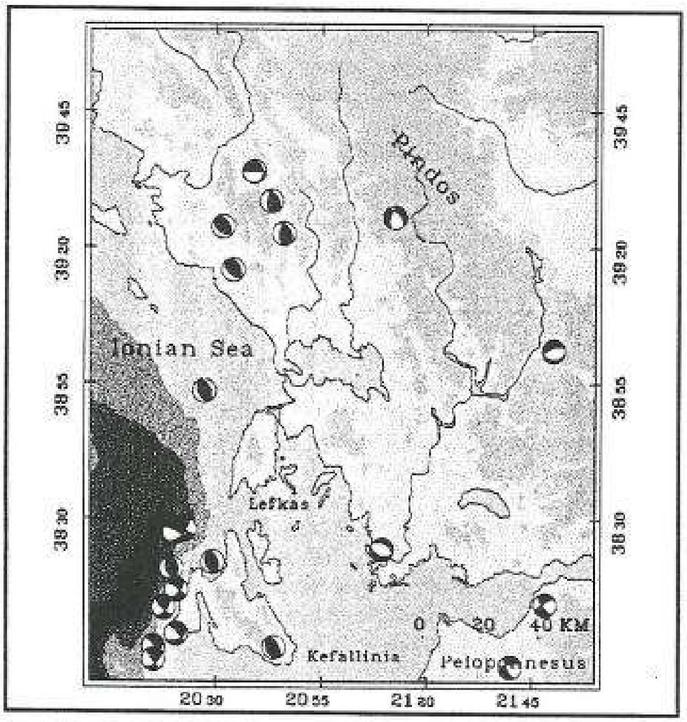


Figure 6. Source mechanisms of large earthquales occurred during 1966-1993, calculated by waveform inversion methods (see text).

The fault plane solutions of large events in the area (fig. 6), indicate mainly right-lateral strike-slip faulting with a thrust component, while others reveal reverse faulting. The P-axes direction is towards the NE. In any case, the pattern between the large and small earthquakes is similar, confirming the complex tectonic regime taking place around Kefallinia island. GPS data results account additionally for an intense dextral strike-slip deformation occurring along the Lixourion-Lefkas fault system (Kahle et al., 1993).

The most accurately located microearthquakes are distributed in dense clusters across the eastern and southern margins of Amvrakikos Gulf, which is rapidly subsiding (IGRS-IFP, 1966). Three clusters can be distinguished. The first is located at the northeastern edge of the gulf, distributed at a mean depth of 18km, characterized by right-lateral strike-slip faulting, considering the NNE-SSW nodal plane as the fault plane, with the P-axes trending NE. Another cluster is located at the south of the gulf around Perganti, distributed at a mean depth of 5km, revealing right-lateral strike-slip faulting on transverse NNW-SSE and NNE-SSE fault planes, the P-axes trending N-S and NE respectively. The sharp dipping of the nodal planes does not allow association between the two clusters, defining thus two zones of complex horizontal shear. Between the two first, a third cluster is observed, distributed down to 14km depth, characterized by normal faulting in approximately E-W direction, the T-axes trending N-S. Beneath this cluster, two dip-slip focal mechanisms with a shallow-dipping plane are observed, reminding the relative pattern seen in Epirus.

Around Trichonis lake, mainly N-S extension is observed, while two reverse focal mechanisms are located deeper.

A kinematic model proposed for the area (Le Pichon et al., 1995) suggests an important transfer zone near Katouna and distributed extension elsewhere. Our results do not support this model, as no sinistral focal mechanisms, that could be associated with the Katouna fault, are observed. On the contrary, if Amvrakikos Gulf acts like a pull-apart basin, the motion should be accommodated by the right-lateral faulting observed. In any case, the pattern in the area appears quite confuse, indicating a complex deformation within a block relatively aseismic, for which ductile processes should play an important role.

CONCLUSIONS

During a two months' microearthquake experiment conducted in northwestern Greece in 1989, 656 events were located. The depth of the locations is limited within the crust, defining the absence of active lithospheric subduction across the area. The microearthquakes are distributed in clusters across the entire area, while aseismic regions are observed, the majority of them associated with active subsidence (Aubuin, 1959; Sorel, 1989), i.e. the Corfu, Lefkada and Kefallinia straits and Amvrakikos Gulf. High activity is observed around Lefkada and Kefallinia islands, defining a large bulk of seismic deformation occurring along the Lixourion-Lefkas transform fault. In Epirus, the seismicity is concentrated across the fold and thrust belt of Morphi-Paramythia-Kourenton, bounded to the west by the continental shelf and to the east by the Pindos mountains. In Akarnania the seismicity is restricted mainly along the eastern margin of Amvrakikos Gulf, around Trichonis lake, while Pindos appears relatively seismic. Comparing the microearthquakes' locations with those of large events occurred in the area (ISC catalogues, M>4), we obtain a similar pattern.

Concerning the focal mechanisms, the pattern is complex, characterized by all types of faulting in close proximity. If we consider the source parameters of large earthquakes, M>5, we obtain a pattern showing compression across Epirus and compression, as well as right-lateral strike-slip motion with a thrust component along Lixourion-Lefkas system and extension along Pindos and the Gulf of Corinth. The transition from ENE shortening across the external zone to N-S extension seen elsewhere in Greece to north Peloponnesus, should account for a small scale internal block deformation characterized by complex shear and rotational processes reflected by the "peculiar" microearthquakes' mechanisms.

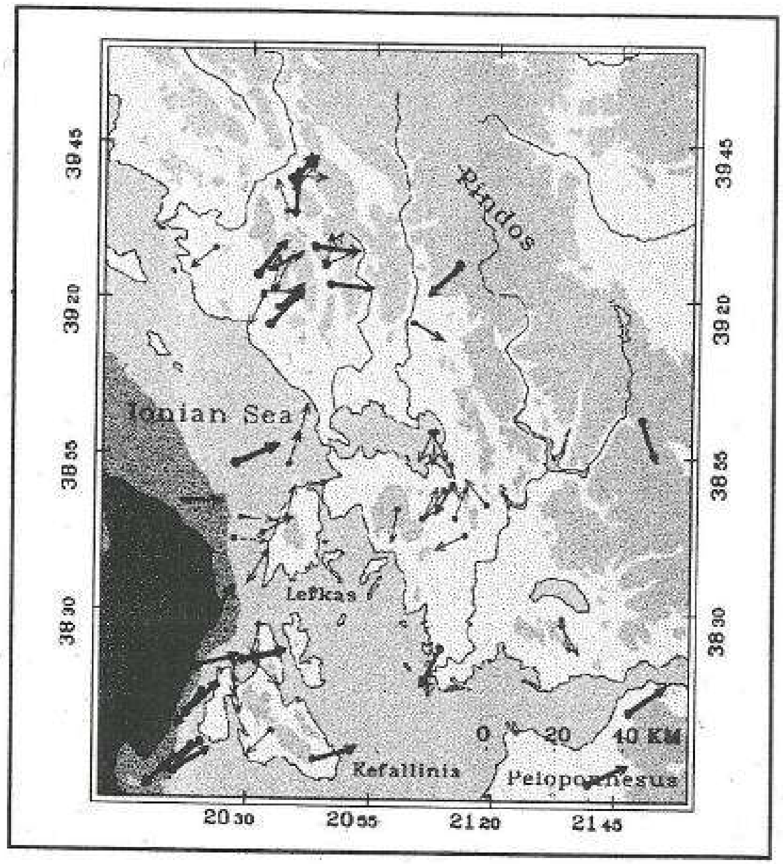


Figure 7. Horizontal projection of the calculated slip-vectors for large and small earthquakes. The thick arrows represent large events, while the thinner represent microearthquakes (quality 1 fault plane solutions).

The horizontal projection of the slip vector of large and small earthquakes (fig. 7) is considered, in order to define the relative motion between the African and Eurasian plate in the area. Considering the slip vector corresponding to fault planes associated with active tectonic features in the area and results of geodesy studies, we obtain a consistent pattern between large and small earthquakes, indicating kinematics toward the NE-SW direction. In the case where the deformation shows normal and reverse faulting in close vicinity, the orientation of the slip vector is reversed but the direction is NE-SW. West of Lefkada the kinematic field changes from the NE-SW to E-W direction. In Akarnania, the pattern is consistent with geodesy measurements, indicating a southwestward motion, when the deformation occurs on dextral transform or north dipping normal faulting. However, the deformation pattern appears confuse in this area, suggesting further investigation.

Concluding, we suggest that a large scale mechanism is responsible for the deformation across northwestern Greece, leading from ENE trending shortening in a western external zone to NNW trending extension in an internal zone. The trend of the shortening or the extension is independent of the type of convergence (continental collision or active subduction), suggesting that the transform Lixourion fault is not a major structure which could disturb the stress pattern in the area. If we take into account recent Satellite Laser Ranging (SLR) measurements indicating that Epirus is almost stable relative to Eurasia , we could suggest that the motion toward the NE-SW direction is associated with a slow continental convergence across the area.

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