Microseismicity and strain pattern in northwestern Greece

Denis Hatzfeld, Iannis Kassaras, Dimitris Panagiotopoulos, Daniel Amorese, Kostas Makropoulos, George Karakasis, and Olivier Coutant

Abstract. During a 7-week microearthquake experiment conducted in Epirus, Akarnania, and the Ionian islands of western Greece, we located approximately 600 earthquakes with magnitudes between 2 and 4.2. No event was deeper than 40 km. The seismicity cannot be clearly associated with any single fault except the Lixourion right-lateral fault located west of the Ionian islands. Focal mechanisms of about 100 earthquakes show, for a narrow band of earthquakes located along the coast, ENE-WSW shortening consistent with the surface tectonics. Further east, focal mechanisms show NNW SSE extension beneath the foothills of the Pindus mountains, which is unrelated to surface faulting but is consistent with the presently subsiding basins. This strain pattern is seen far north and south of the Lixourion fault and is similar to the one observed in the Peloponnesse. It suggests that a large scale mechanism is responsible for the recent geodynamics of both the northwestern and southwestern Aegean.

Introduction

Continental deformation is more complex than plate tectonics predicts because deformation is not confined to one plate or a narrow zone, because the observed strain varies across the active region, and because ductile deformation seems to play an important role [e.g., Mohr and Tapponnier, 1975: McKenzie, 1978]. Moreover, the entire lithosphere does not behave as a rigid plate [e.g., England et al., 1985]. This is especially clear for regions which involve closure of oceanic domains, as in the Mediterranean where the oceanic floor has almost completely disappeared since the Miocene time [Dewey et al., 1975; Tapponnier, 1977; Philip, 1987].

Some measure of crustal deformation is generally deduced from tectonic observations, seismicity, and now satellite geodesy, but each technique suffers from limitations when attempting to describe the total deformation. A homogeneous sampling in space and time of the tectonic observations (fault trend, motion or striations) is uncommon, and discerning temporal and spatial variations in the strain pattern is sometimes difficult [Jackson et al., 1982; Mercier, 1983]. Focal mechanisms computed with teleseismic data are available only for those rare earthquakes of magnitude greater than 5.5, so in regions of moderate seismicity and small dimension, it is not possible to infer a continuous strain pattern for the brittle part of the deformation. Space geodesy has just started to provide an accurate and detailed map of deformation over large areas.

Rapid and intense deformation characterizes the Aegean region located between the two major lithospheric plates of Africa and Europe. Because of its small dimensions relative to other regions where continental deformation occurs (e.g., Tibet) and because the vertical dimension is not negligible compared to horizontal dimensions, a detailed study of active deformation in the Aegean can assist us in understanding the mechanisms governing continental tectonics.

Northwestern Greece plays a pivotal role in most of the geodynamical models of current deformation in the Aegean. It is close to the pole of rotation that Le Pichon and Angelier [1979] and Le Pichon et al. [1995] proposed for the Hellenic trench and therefore the deformation should vary spatially. It should undergo E-W shortening according to the "broken slat" model of Tsezun et al. [1991]. Most of the NW-SE structures should be left-lateral reverse faults as in the model of King et al. [1993]. Furthermore, it lies near the transition between a zone of active subduction located just south of the Ionian islands at the Hellenic trench and a region where continents collide in Apulia and northern Greece [i.e., McKenzie, 1972]. It is moreover bounded by the important Lixourion dextral strike-slip fault located west of Kefallinia [Cushing, 1985; Sorel, 1989].

Tectonic observations as well as focal mechanisms of strong earthquakes show clear NE-SW shortening in the external part of the Hellenic arc along the trench and N-S extension in more internal positions such as in the Gulf of Corinth [McKenzie, 1978]. The transition between compression and extension, however, is not precisely located. Two microearthquake studies conducted in Epirus [King et al., 1983; Kirati et al., 1987] show complicated patterns of both the seismicity and the focal mechanisms. No clear general pattern about the deformation of this area was shown.

This paper describes the results of a microearthquake study conducted in Epirus and Akarnania, near the transition between active oceanic subduction and continental collision.

Geodynamics and Tectonics

The Hellenides mountains mark the southern continuation of the Albanides and Dinarides [Aubouin, 1959]. Within the Albanides and Hellenides, the Pindus mountains are located between southern Albania and the Gulf of Corinth. To the northwest of the Pindus, a regular succession of ridges (with a mean elevation of about 1000 m) trending NNW, separated by narrow valleys, gives way farther west to flat topography.
Toward the south, across the Amyvakhos Gulf, Akarnania does not show similar topography. The southern boundary of Akarnania is the Gulf of Patras, which is undergoing significant N-S extension.

The Hellenides, which consist of roots mainly formed during the Mesozoic and Cenozoic times, are considered to be a typical fold and thrust belt due to the shortening of a passive continental margin [i.e., Aubouin, 1965; Institut de Géologie et de Recherches du Sous-sol-Insitut Français du Pétrole, 1966; British Petroleum., 1971]. Sediments are of considerable thickness and the basement in some places can be located at a depth of 10 km or more. In the external Hellenides, evidence for tectonic activity before the late Oligocene early Miocene times has not been observed [Aubouin, 1973; Thébault, 1982], and the total amount of shortening is probably several hundreds of km [IGRS-IFF, 1966; Waters, 1993].

Since Miocene time, tectonic activity in northwestern Greece has been rather complex [Mercier et al., 1976]. Compression is seen in Epirus at or near the middle Miocene time and is likely to have been associated with the jump of the active thrusting from the Pindus to the Ionian zone. Compression occurred again around the lower Pliocene time and is probably contemporary with the initiation of the Lixourion dextral strike-slip fault located west of Lefkada and Kefallinia. Finally, compression is also seen during the middle Pliocene time. The question of discontinuous episodes or continuous tectonics is still a matter of debate [Jackson et al., 1982; Mercier, 1983; Underhill, 1989; Waters, 1993].

The present convergence rate between the two major plates of Africa and Europe is about 1 cm/yr [Argus et al., 1989], but the relative motion across the Hellenic trench is certainly larger [Jackson, 1994; Le Pichon and Angelier, 1979] due to the active subduction of African lithosphere beneath the Aegean [Papazachos and Comninakis, 1971]. This active oceanic subduction progressively becomes continental convergence in northwestern Greece and Albania [McKenzie, 1978], and the transition is probably located around the Zakynthos island.

Active tectonics shows reverse faulting on a broad scale around the Ionian islands [Cushing, 1985; Sorel, 1989; Underhill, 1989; Doutso et al., 1987; Brooks and Ferron, 1984], but well documented reverse faulting affects mainly the westernmost part of Epirus and Akarnania [Sorel, 1989]. Actually most of the active tectonics is extensional, in Epirus, where is seen widely [Waters, 1993] as well in Akarnania, beneath the Amyvakhos Gulf, the Aoetos valley, and the numerous lakes [Sorel, 1989; King et al., 1993; Doutso et al., 1987; Underhill, 1989] or the Gulf of Patras [Ferron, 1985; Chronis et al., 1991]. However some of the faults could be anclitic faults related to regional compression [Waters, 1993].

The large earthquakes are located around the Ionian islands and show predominately reverse faulting. Dextral strike-slip is observed for earthquakes located west of Lefkada and Kefallinia and normal faulting in continental Greece [McKenzie, 1972; 1978; Anderson and Jackson, 1987; Kiratsis and Longston, 1991; Scordills et al., 1985]. Paleomagnetic observations demonstrate, in agreement with tectonic data, that no significant rotation has affected the northwestern part of the Aegean arc during lower Cenozoic time [Horner and Freeman, 1983; Kissel et al., 1985]. They also clearly show that Epirus, Akarnania, and Albania have rotated as a whole since upper Oligocene. A first 25° clockwise rotation occurred probably during middle Miocene and a second phase of the same amplitude during the Plio-Quaternary [Kissel et al., 1985; Speranza et al., 1995]. The different geological structures were then trending almost E-W 15 m.y. ago.

Data

During the summer of 1989 (from July 5 to August 22), we operated a network of 31 seismograph stations around Epirus, Akarnania, and from Kefallinia to Corfu. This network was equipped with Sprengnether MEQ800 smoked paper instruments connected to 1-Hz Mark Product vertical seismometers (Figure 1). The spacing between stations was about 15 km in order to survey the whole region (about 200 km x 120 km) and to compute crustal focal mechanisms. In total we gathered 1150 smoked paper records and read a total of about 9000 P and 3000 S wave arrival times. We will not describe extensively the procedure adopted to choose a velocity structure (Table 1), compute a mean Vp/Vs ratio of 1.82, locate the earthquakes, and ensure accuracy and reliability of the earthquake locations. Details can be found in several previous papers [e.g., Hatzfeld et al., 1990] Among the 656 events, we located 490 earthquakes with an accuracy estimated to be better than 8 km and 277 earthquakes better than 4 km. The magnitude was calculated using the coda duration [Lee and Lahr, 1972].

The duration of our experiment was about 7 weeks, and thus there are aspects of the seismicity that are not representative of long periods of time. On the other hand, this disadvantage is offset by the greater accuracy of our locations and focal mechanisms. It is, however, necessary to respect some rules to obtain significant information from small magnitude earthquakes: (1) no composite mechanisms are computed; (2) because microearthquakes are related to faults of small dimension (usually smaller than a few hundreds meters), regional deformation is never inferred from one focal mechanism alone and observations are smoothed over a scale of a few tens of kilometers; (3) where we have mechanisms of stronger earthquakes, those of microearthquakes should be consistent with them.

We assigned a degree of confidence depending on the uncertainties in the solutions: category 1 for which the orientations of both planes are constrained better than 20° (8 P waves polarities sample 3 quadrants), category 2 with only one plane constrained better than 20° (8 polarities sampling 2 quadrants), and category 3 for which first motions give only an indication of the style of deformation that occurred. We computed a total of 120 mechanisms: among them, 50 belong to category 1 and 51 to category 2 (Appendix and Table 2).1

1Data are available upon request. Order from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009. Document 795-001; $2.50. Payment must accompany order.
Results

Among the 656 earthquakes that we located, 459 occurred within the network in clusters with gaps between them (Figure 2). The magnitudes of the earthquakes range from 0.9 to 4.2 with most between 2 and 3.

The first main result is that the deepest reliably located event is shallower than 40 km. Therefore no earthquake can be related to an active lithospheric slab beneath Epirus, Akarnania, or the Pindus mountains contrary to observations beneath the Peloponnese, where we located earthquakes at a depth of 150 km, or beneath the Gulf of Corinth, where they reach a depth of 70 km [Hatzfeld et al., 1990]. This was also the conclusion from reliable teleseismically located events [Hatzfeld and Martin, 1992].

The second point is that shallow seismicity is not uniformly distributed over northwestern Greece. The seismicity is bounded to the east by the Pindus mountains and on the west by the continental shelf (defined by the 1000 m isobath). This is similar to the earthquakes located teleseismically by the International Seismological Center (ISC) and therefore not an artifact due to the location of our seismological network. On a rough scale we observe two different seismic regions (Epirus and Akarnania) separated by the aseismic Amvrakahos Gulf. These regions also have different tectonics and morphology and we will consider them separately. Significant seismicity is observed around the Ionian islands (Lefkada, Kefallinia, and Ithaki).

A map of all the fault plane solutions (Figure 3) that we computed for earthquakes in northwestern Greece shows a complicated pattern with predominantly reverse faulting in western Epirus and normal faulting inland. Around the Ionian islands we observe reverse, normal, and strike-slip faulting. Around the Amvrakahos Gulf and lake Trikhoris, mechanisms suggest mainly normal faulting.

Epirus (Figures 4, 5, and 6)

In Epirus, seismicity is restricted to the fold and thrust belt located west of the Pindus mountains (the Botzara, Kassidieres,

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Paranythia, Kourenton, and Louros mountains). The Pindus mountains themselves, as well as the regions of low topography such as Parga and Parapotamos, are of low seismic activity (Figure 4). Very little activity is observed between the coast and the islands of Paxi and Corfu, in agreement with the ISC locations.

In northern Epirus (Figure 4), one cluster of earthquakes is located between the Kassidiates and the Kourenton anticlines, which are bounded by reverse faults dipping east and west, respectively [IGRS-IFP, 1966], some of which are inferred to be active [King et al., 1993; Waters, 1993], and east of the Soulopoulou offset, which according to King et al. [1993] is a region of rapid subsidence. No fault plane solutions were available for this cluster, and focal depths do not define a dipping zone. West of the Kourenton range, there is another cluster of activity at a depth of about 5 to 8 km. We computed 12 mechanisms for this cluster (#160, 210, 416, 418, 426, 430, 432, 439, 441, 449, 451, 602) showing mainly normal faulting, with T axes trending N-S, and a slight component of strike-slip faulting for some of them (Figure 5). One other mechanism (#422), computed west of the Pindus beneath the Ioannina basin, also shows N-S trending extension.

We located an E-W trending cluster of earthquakes at the western termination of the Petousi (also called Souli) fault, which has been an active, E-W trending, left-lateral strike-slip fault between the Louros and the Kourenton ranges and is certainly one of the clearest features in the field. It is not clear, if this fault is still active in some places [Sorel, 1989; King et al., 1993; Waters, 1991]. One mechanism (#374) is consistent with left-lateral strike-slip motion on this fault.

South of the Petousi fault, seismicity, with depths ranging from 9 to 14 km, seems concentrated around the Paranythia and Morphi mountains, which in both cases are bounded by reverse faults dipping east [IGRS-IFP, 1966] and inferred to be active [King et al., 1993; Waters, 1993]. Most mechanisms show reverse faulting, with P axes trending NE (#107, 292, 326, 337, 343, 403, 636), but there are also some with a large component of N-S extension or strike-slip faulting (#288, 319, 390, 485). Among the earthquakes located farther east around the Louros range, three mechanisms (#458, 550, 555) located in the northern part, where a reverse fault has been inferred, show a significant component of strike-slip faulting. The other mechanisms (#15, 78, 171, 175, 179, 366, 463) are for earthquakes located farther south. They show dip-slip mechanisms, with a very shallow dipping plane (whose orientation is not very well constrained) trending ESE and dipping north, and are located at depths greater than 18 km.

A section across Epirus (Figure 6), trending approximately parallel to the Petousi fault and perpendicular to the main structures, shows a slight deepening of the best located foci.
from 15 km in the west, to about 25 km in the east. The mechanisms of the shallower earthquakes indicate reverse faulting, but those of the deeper ones, located to the east, show dip-slip with a shallow dipping plane toward the northeast. Above this shallow dipping seismic zone, a cluster of earthquakes located at a depth of about 10 km shows N-S extension. In this region, a complex pattern of seismicity and focal mechanisms was also observed during two previous microearthquakes surveys [King et al., 1983; Kirzi et al., 1987].

The reliable mechanisms of strong earthquakes computed in Epirus are few [McKenzie, 1978; Anderson and Jackson, 1987; Raker et al., 1994] and show mainly reverse faulting (Figure 3). Two Centroid Moment Tensors (CMT) solutions also show reverse faulting, with the P axes trending NNE. One solution shows normal faulting, with the T axis trending almost E-W, which is inconsistent with our observations (Figure 3).

The Ionian Islands (Figures 7, 8, and 9)

We observe significant seismic activity around the islands of Kefallinia and Lefkada, which have both experienced strong earthquakes in the recent past. The seismicity is restricted to the two islands, with no earthquakes located beneath the deep basin west of the islands.

Around Lefkada, focal mechanisms show mainly strike-slip faulting, with one plane trending NNE. Most solutions (#23, 313, 339, 354, 378, 464, 503, 545, 593, 650) show right-lateral slip, consistent with the mechanisms observed for most of the strong earthquakes in this area. These events could be related to the active right-lateral strike-slip faults of Athanion and Agios Nikitas observed west of Lefkada [Cushing, 1985; Sorel, 1989; Underhill, 1989], which are about 50 km long. In the same area, mechanisms based on telesismic data [Scordilis et al., 1985; Papadimitriou, 1988; Anderson and Jackson, 1987; Baker et al., 1994] also show right-lateral strike-slip faulting on a NE striking fault plane (like the Lixouri-Lefkada fault, Figure 1) west of Lefkada. But the westernmost mechanisms (#195, 219, 495, 591), located to the west of the Lixouri fault, show left-lateral strike-slip faulting. They are located at depth of about 30 km, whereas most of the earthquakes beneath Lefkada are shallower than 20 km.

The level of seismic activity is higher around Kefallinia than around Lefkada. During our experiment, we recorded about
150 events up to magnitude 4 in this area. No clear relationship with surface faulting was observed. A dense cluster is located west of the island, beneath the Gulf of Aegina Kiriaki, but seismicity is spread over most of Kefallinia. Fault plane solutions exhibit a wide range of mechanisms. We observe reverse faulting (#38, 57, 189, 194, 203, 213) with \( P \) axes trending mostly NE and strike-slip faulting (#10, 116, 421, 434, 482, 494, 531), dextral if the N-S trending plane is the fault plane (consistent with observations from Lefkada). A few events show a large component of normal faulting. This pattern is rather complex, but most of the \( P \) axes trend NE, consistent with the mechanisms of strong earthquakes [e.g., Kiratzi and Langston, 1991; Baker et al., 1994]. The depths of the events are relatively shallow (less than 20 km) and cannot be associated with any active fault. Both the shallow depths and the complexity are not surprising, because Kefallinia lies near the front edge of the zone of convergence, and the tectonics are probably quite complex, possibly with compressional reactivation of previous normal faults [Sorel, 1989; Underhill, 1989].

In the area of the Ionian islands, the seismicity located by the ISC lies mainly west of the islands, beneath the deeper bathymetry. Therefore if the locations that we obtained are representative of the area's seismic activity then there is a systematic offset of about 10 km between the locations of microearthquake and strong earthquake activity, or the strong events have been systematically mislocated. On both ends of the Lixouri fault, focal mechanisms computed teleseismically show reverse faulting for earthquakes located north and south. The ISC has reported almost no seismic activity between the Ionian islands and the Peloponnese, which is consistent with the results of another microearthquake study conducted in the Peloponnese during the summer of 1986 [Hatzfeld et al., 1990]. There is obviously a lack of seismicity in this region.

**Akarnania (Figures 7, 8, and 9)**

In Akarnania, the seismicity is spread into several clusters that are not restricted to ranges as in Epirus. A dense cluster is located east of the Amvrakikos Gulf. Mechanisms in the northern group (#74, 514, 517, 612) show mainly strike-slip faulting, with right-lateral slip if the north striking plane is chosen and with the \( T \) axes trending NW. Those in a southern group (#22, 32, 48, 330, 470, 625), show normal faulting, with \( T \) axes trending NNW-SSE. These events are located beneath the Katouna valley, which is an important active left-lateral transfer zone [Melis et al., 1980; Sorel, 1989; Brooks et al., 1988; Underhill, 1989], but our mechanisms are not consistent with strike-slip motion on a fault trending along the Katouna valley. Another cluster is located south of the Amvrakikos Gulf around the Pergandi mountains. Five mechanisms (#327, 405, 427, 635, 639) show strike-slip
faulting consistent with the mechanisms observed west of Lefkada and east of the Amvrakikos Gulf, i.e., with the T axes trending NW. Minor activity is also observed beneath the Pindus mountains, but because of the network's location, we were unable to compute mechanisms in this area.

Around Lake Trikhone, most mechanisms (#47, 80, 81, 82, 87, 621) are consistent with normal faulting, with the T axes trending NNW. Only two mechanisms are reverse; one is slightly outside of our area (#76), the other is 26 km deep (#492), and the P axes trend NE. Not many strong earthquake mechanisms are available in this area. The only strong earthquake solution is for February 5, 1966, which occurred near the Kremasta dam and is thought to be associated with the filling of the reservoir. The computed mechanism [McKenzie, 1972; Anderson and Jackson, 1987] shows normal faulting with the T axis trending N-S. The CMT solutions computed for this area (Figure 3) show normal faulting, with the T axes trending NNE.

**Discussion**

Reverse Faulting Versus Normal Faulting

Around the Ionian islands the microseismicity is restricted to the emerged land or to areas of shallow bathymetry (less than 1000 m) and is therefore somewhat to the east of where strong earthquakes are commonly located. The seismicity west of Lefkada is related to the Agios Nikitas right-lateral fault which probably belongs to the Liakourion fault system, and it is likely that this 50-km-long system of faults plays some role in the kinematics of this area. This right-lateral motion is consistent with tectonic observations in Lefkada [Cushing, 1985; Sorel, 1989; Underhill, 1989], with the mechanisms of some strong earthquakes [e.g., Anderson and Jackson, 1987; Kikuchi and Langston, 1991], and with geodetic measurements [Kahle et al., 1993]. The strongest earthquakes of the Aegean have occurred beneath or near the Ionian islands, not only during the last century but also further back in historical time [Papazachos and Papazachou, 1989]. This is the only clear, important strike-slip fault zone around continental Greece, and one possible reason for this large seismic activity could be that seismic energy release is greater for strike slip faults, as it is observed for the north Aegean sea [Jackson and McKenzie, 1988].

Further south, around Kefallinia, the focal mechanisms are not so clear. There are indeed some strike-slip faulting events, but these are mixed with both reverse and normal faulting events. Most of these mechanisms show either NE trending P axes or NW trending T axes. The reverse faults are located at a
mean depth of 11 km, the strike-slip mechanisms at a mean depth of 13 km, and the normal faults at a mean depth of 15.5 km. In Kefallinia, tectonic observations do not show clear strike-slip faulting but instead normal faulting during the Miocene followed by reverse faulting since the lower Pliocene [Mercier et al., 1979; Sorel, 1989; Underhill, 1989]. Geodetic observations also show a slight component of convergence across the region [Veis et al., 1992; Kähle et al., 1993]. The strain pattern deduced from the microseismicity beneath Kefallinia is more complex than the one beneath Lefkada and is consistent with the present deformation which is relatively modest in the whole area [Sorel, 1989]. The focal mechanisms of strong events show also strike-slip faulting west of Kefallinia but south of it only reverse faulting [McKenzie, 1978; Anderson and Jackson, 1987]. A detailed study of coastal uplift due to the strong (Ms=7.2) 1953 earthquake [Siros et al., 1994] is consistent with a strike-slip mechanism including a slight component of reverse faulting [Papazachos et al., 1994]. The transition between strike-slip faulting and reverse faulting is probably located just south of Kefallinia where the bathymetry exhibits a change in strike.

The seismicity located north of Lefkada (Figure 2) does not help to define precisely the boundary between oceanic subduction and continental collision. North of the Lixourion
fault, seismicity is restricted to the 60-km-wide thrust and fold belt seen in northwestern Greece and western Albania. South of the Lixourion fault, actually south of Zakynthos, the seismicity defines more clearly the active trench. The northern continuation of the dextral strike-slip Lixourion fault marks a possible boundary in the seismicity on the mainland, because south of the continuation of the fault, the Pindus is seismically active, whereas north of it, it is not (Figure 2).

The Kefallinia and Zakynthos basins are aseismic. Brooks et al. [1988] proposed a model explaining this lack of seismicity by a block moving southwestward and bounded to the west by the dextral strike-slip Lixourion fault and to the east by the sinistral strike-slip Katouna transfer zone. This model is consistent with the bulk rotation of the Ionian block proposed by Le Pichon et al. [1994] on the basis of geodetic measurements. It suggests an important transfer zone near Katouna (the Amvrakikos Gulf and the Triphonis lake acting as pull-apart basins) and distributed extension as far south as the plain of Olympia. But both microearthquake and strong earthquake mechanisms do not show evidence to support this.

**Figure 8.** Map of the focal mechanisms computed for Akarnania and the Ionian islands (same format as Figure 5).

**Figure 9.** Section across the Ionian islands and Akarnania.
model because we do not observe sinistral strike-slip focal mechanisms associated with the Katouna fault system.

In Epirus, the Petousi (or Souli) fault trends WSW and cuts all the folds but does not seem to be an important seismically active strike-slip fault, though we computed one strike-slip focal mechanism for an earthquake at its western termination. We also observe a lack of seismicity for the E-W trending Spartilas strike-slip fault mapped in Corfu [Janet, 1982; Caputo, 1988; Doutsos and Frydas, 1994].

Seismicity may be related to some NW trending reverse faulting only in western Epirus, near the Paramythia fault. Toward the east, where recent reverse faults are inferred in the field on the basis of geomorphology or antithetic normal faults [Waters, 1993], we did not obtain any evidence of reverse focal mechanisms. On the contrary, we computed normal focal mechanisms, with T axes trending roughly N-S, for earthquakes around the subsiding Soulopoulou basin [King et al., 1993].

A section across Epirus (Figure 6) shows that seismicity defines a zone that dips less to the east as a listric fault. On the west the steep portion is associated with reverse faulting, but in the east the shallow dipping part is associated with dip-slip faulting. A cluster of earthquakes showing normal faulting mechanisms is located above the shallow dipping faulting. This pattern is similar to that observed for former normal listric faults when they act as reverse faults. This creates a large-scale fold, and shallow local extension is observed at the top of the fold as during the El Asnam earthquake [Philip and Meghraoui, 1983]. But here this should be taken with some caution, because the three types of mechanisms are not observed exactly in the same places.

In both Epirus and Akarnania, there are common features: the largest subsiding basins, such as Corfu Strait, Amvrakikos Gulf, Agrinion basin, Kefallinia and Lefkada Gulfs, are aseismic. This is not necessarily an artifact due to the short time of our observations, because this is also observed for the ISC catalogue and for the historical seismicity [Papazachos and Papazachou, 1989; Institute of Geology and Mineral Resources, 1988]. The subsidence of these basins probably started during Pliocene and continues at present time [Aubouin, 1959; Sorel, 1989], but the deformation is small and not accommodated by large normal faults as in the Gulf of Corinth.

Figure 10. Map of the principal axes of deformation deduced from the focal mechanisms. Thin lines are from this study, and thick lines are either for body wave modeling of earthquakes [Baker et al., 1994] or CMT solutions. We show the horizontal projection of the axes which plunge less than 45°: (a) P axes; (b) T axes. The uniform strain pattern seen both for P and T axes is not disturbed by the Lixourion fault and suggests that a mechanism of large scale is responsible for the geodynamics of the area.
To summarize, we observe reverse faulting in two regions: south of the Ionian islands where active oceanic subduction takes place and west of Epirus where it affects the western part of the fold and thrust belt and is due to continental collision. In addition, we observe NNW trending extension all along the foothills of the Pindus mountains.

**Direction of Shortening and Extension**

A plot (Figures 10a and 10b) of the shallow dipping $P$ and $T$ axes provides information about the mean pattern of deformation. We plot orientations only for mechanisms of earthquakes deeper than 5 km, because shallower mechanisms are questionable and could be mislocated and to avoid any misinterpretation due to the deformation of the thick evaporite layer. This information should be smoothed in space to get a mean strain pattern. We add to our mechanisms those computed using body waves modeling [Baker et al., 1994] and the currently available CMT solutions.

We observe consistency between most of our solutions and the other solutions, lending confidence to the use of earthquakes with magnitudes smaller than 5. The $P$ axes mostly trend WSW all along the Ionian islands and within western Epirus as far south as the Amvrakikos Gulf. This trend of $P$ axes is the same not only for the reverse faulting in Epirus and the Ionian islands and for the strike-slip mechanisms of the Lixouri fault but also for earthquakes in the northern Peloponnese [Hatzfeld et al., 1990]. This orientation of $P$ axes, however, differs from that along the southern Hellenic trench, from southern Peloponnese to Rhodes, where it trends NNE [Hatzfeld et al., 1993]. The $T$ axes consistently trend NNW from northern Epirus to southern Peloponnese. Around the Ionian islands, there is a slight shift in the azimuth toward the west, which is probably due to the Lixouri fault.

Our data are located west of the Pindus and therefore we cannot relate our results to the broken slats model of Taymaz et al. [1991]. In their model, the western margin of Greece rotates clockwise relative to Apulia, which accommodates E-W shortening; central Greece is an assembly of several slats trending WNW, and between these slats extension is trending NNE. Our data support in detail neither the model proposed by King et al. [1993] because left-lateral strike-slip motion along NNW faults is very seldom observed, nor the bulk clockwise rotation of northwestern Greece around a pole located in southern Italy proposed by Le Pichon and Angelier [1979] or Le Pichon et al. [1993], because compression is observed only in a few places without any clear change in the orientation of the $P$ axes.

Geodetic Satellite Laser Ranging (SLR) measurements [Noomen et al., 1994; Robbins et al., 1994] clearly show that Karitsa in Epirus is almost stable relative to Europe but
Christallaria in southern Peloponnese moves SW with a velocity of 4 cm/yr. These measurements are consistent with a slow continental convergence in the north and a fast oceanic subduction in the south, the Lixourion fault being an active transform fault. But on the other hand, we observe a remarkable consistency in the deformation deduced from focal mechanisms over the whole western Hellenic arc (from Albania to southern Peloponnese). Toward the western external part, along the front of the arc, ENE trending shortening is seen within a narrow band. In a more internal position, we observe NNW trending extension along the whole boundary. The trend of the shortening or the extension is independent of the type of convergence (continental collision or active subduction) and thus suggests that the Lixourion fault is not a major transform zone which would disturb the stress pattern. On the other hand, the continuity in the deformation across such an important and shallow structure suggests a mechanism of large scale and implies some ductile deformation.

Conclusion

The microearthquakes that we recorded during 7 weeks help define the kinematics of deformation in Epirus, Akarnania, and the Ionian islands. The seismicity is restricted to the fold and thrust belt in Epirus but extends to the Pindus mountains farther south. Most of the subsiding basins are aseismic, in contrast to the Corinth Gulf. The Lixourion fault is an important dextral strike-slip fault located between continental collision to the north and active subduction of oceanic lithosphere to the south. But the type of deformation, ENE shortening in the external zone and NNW extension along the foothill of the Pindus, both for small and for strong earthquakes, is seen along all of western Greece, from Albania to Peloponnese, consistent with the uniform paleomagnetic rotations [Kissel et al., 1985; Speranza et al., 1992]. It suggests that mechanisms active over a broad scale are responsible for the geodynamics of the area.

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D. Amorese, O. Coutant, and D. Hatzfeld, Laboratoire de Géophysique Interne et Tectonophysique, Observatoire de Grenoble, BP 53, 38041 Grenoble Cedex 9, France. (e-mail: hatzfeld@lggt.observgr.fr) G. Karakaisis and D. Panagiotopoulos, GeophysicalLaboratory, Aristotelian University, P.O. Box 352-1, 54006 Thessaloniki, Greece. (e-mail: gkarakaisis@olymp.ece.auth.gr) I. Kassaras and K. Matakopoulos, Department of Geophysics, University of Athens, 15784 Ilissia, Athens, Greece. (e-mail: geol12@atlas.uaa.aradne-t.gr)

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