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The Hellenic subduction beneath the Peloponnesus: first results of a microearthquake study

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A preliminary examination of the 1070 earthquake locations, determined from 6 weeks of recording in 1986 by 46 stations, show that the seismicity is spread over a wide area of the Peloponnesus and the western Hellenic arc and throughout the whole crust No clear individual faults can be identified from the seismicity, but clusters of activity are observed in some places. Seismicity is concentrated above 40 km and deeper earthquakes were not numerous. Only 28 of the 466 events with uncertainties in depth less than 5 km occurred deeper than 40 km

Seismicity deeper than 30 km defines a flat zone at a depth between 40 km and 70 km, starting from the trench to about 200 km towards the northeast. Further northeast, the dip of the seismic zone abruptly changes to 45° Fault plane solutions for the deeper events, generally indicate T-axes plunging northeast, within the subducted slab Therefore, we interpret the seismicity deeper than 30 km as due to the superposition of two different causes (1) the steep zone is due to the subduction of the African lithospheric plate beneath the Aegean, and (2) the shallow flat zone located between the trench and the Argolide is partly due to the loading of the overriding Aegean plate which is deforming above the African plate

1. Introduction

The Aegean area is one of the most active seismic zones within the Mediterranean. The tectonics are rather complex due to the interaction of the convergent relative motion of the Eurasian and African plates with the intense internal deformation in the inner part of the Hellenic arc [1–4].

Seismicity clearly defines an active belt on the inner wall of the Hellenic trench and a dipping zone of intermediate seismicity [5]. But interpretations differ about the exact shape of the subducted slab: a symmetrical amphitheatrical shape [6] or a deepening towards the east [7].

The shallow historical seismicity is quite scattered over the whole area with higher concentration along the Hellenic trench, the Gulf of Corinth, the Pindus massif and over the Dodecanese islands. Around the Peloponnesus the seismicity seems more intense in the western part, but the lack of a dense regional seismic network as well as probable strong heterogeneities in the velocity structure have not yet allowed a detailed tectonic interpretation.

Focal mechanisms have been computed, using polarities of long-period WWSSN dat, e.g. [1,2,8] or of other data [9–11]. The earthquakes of the Hellenic trench clearly show reverse faulting, usually with a shallow dipping plane and the slip vector trending NE–SW. The shallow events within the Aegean Sea or the Peloponnesus are dominated by extension in various directions. Very few fault plane solutions are available for intermediate depth events [2,8], probably because of the scarcity of local stations and the relatively low magnitude of the earthquakes.

We intended to improve the accuracy of earthquake locations and increase the number of fault

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plane solutions in the western Hellenic arc, beneath and around the Peloponnesus. Our purposes were to define better the shape of the subducted slab, and to evaluate the orientation of the strain above and within the slab in order to constrain better geodynamical models for this area.

Tectonic studies in this area show a complex deformation pattern both in space and time [3,4] as well as local block rotations [12], internal deformation [13], and locking of the subduction south of the Ionian islands [14]. During the Quaternary period there has been N–S extension across the Gulf of Corinth and within the northern Peloponnesus, and E–W extension in the southern Peloponnesus. This is consistent with fault plane solutions in these areas [2,15–18].

In this paper we will present briefly the preliminary results of a microearthquake study conducted over the Peloponnesus and focus particularly on the intermediate seismicity.

2. The experiment

During the summer of 1986 (4 June to 17 July) we installed 46 portable seismological stations—41 smoked paper recorders (Sprengnether MEQ 800) connected to a 1-Hz seismometer and 5 digital magnetic tape recorders (IPG Strasbourg) connected to a 2-Hz, 3D seismometer—over the Peloponnesus, across the Gulf of Corinth and on a few surrounding islands (Kefallinia, Levkas, Zakynthos, Strophades, Kythira and Antikythira). We had to deal with two problems: (1) in order to obtain a complete view of the seismotectonics we had to cover the whole area. But (2) because of logistic problems and also to determine reliable fault plane solution for shallow earthquakes, the spacing between stations had to be smaller than the mean depth of the earthquakes. The number of stations and their geographical distribution were designed to achieve both objectives (Fig. 1).

The smoked paper instruments were run at 60 mm/minute, and every two days we visited the stations to change the record, to measure the internal clock drift, and to check and calibrate the instrument. Data from the permanent stations of the National Observatory of Greece were also included.

During the 45 days of the experiment we

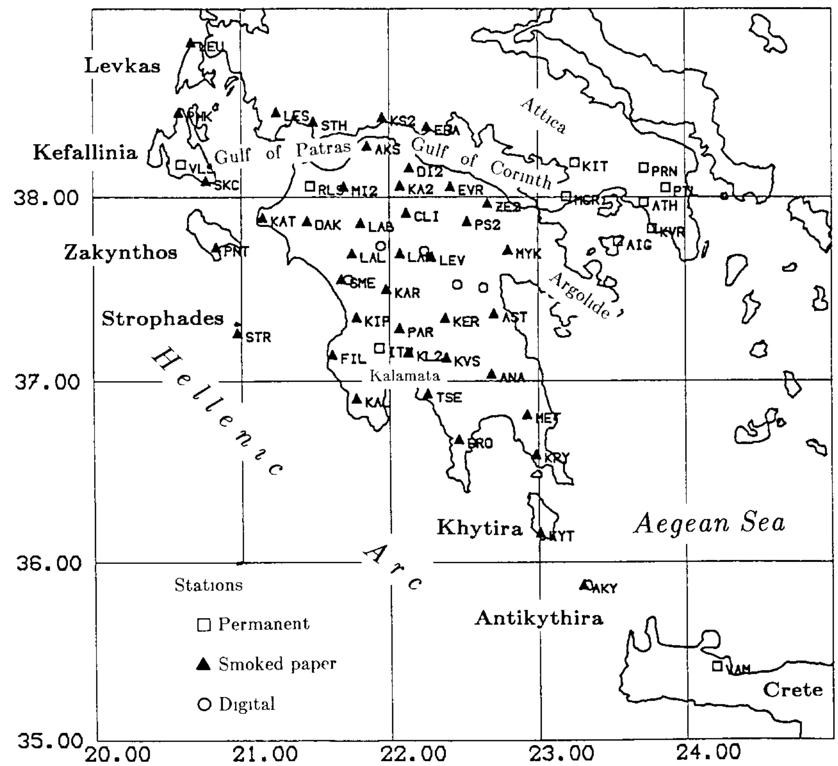

Fig. 1. Map of the seismological stations and geographical names.

gathered about 650 seismograms. Times were measured using a magnifying lens, allowing an accuracy of 0.05 mm. We believe that the total amount of uncertainty in times including clock drift, error in reading, variations in drum rotation or in paper length, is smaller than 0.2 s. We read 13,798 P arrival times and 4814 S arrival times.

3. Location procedure, and fault plane solutions

We will describe only briefly the procedure, a detailed discussion can be found in [19].

First, we located 1070 earthquakes, each recorded by a minimum of 5 stations, using the program HYPO71 [20] and flat layered velocity structures. We used a value of 1.79 ± 0.02 for the V_p/V_s ratio, computed from 97 individual Wadati plots. We separated the earthquakes into four different subsets according to their epicenter and depth: the Peloponnesus, the Hellenic trench, the Gulf of Corinth, and the events deeper than 40 km. For each subset we investigated for the velocity structure (with a maximum of 4 layers) that minimized the residuals.

Second, to evaluate uncertainties in earthquake locations, we adopted the following procedure: instead of computing tests with synthetic data, we preferred to locate our earthquakes in various reasonable velocity structures. We selected as reliable events, those with a minimum of 8 P and 1 S whose relocations differ by less than 10 km, and by less than 5 km in both epicenter and depth. From the total number of recorded earthquakes, 699 were relocated better than 10 km, and 466 better than 5 km, using different velocity structures, and therefore can be considered as reliably located events (Fig. 2).

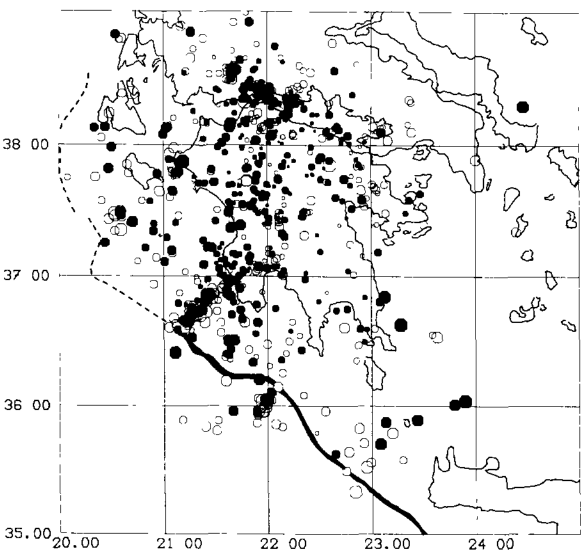

Fig 2 Seismicity map of the 699 earthquakes whose location accuracy is thought to be better than 10 km (black dots are better than 5 km). The size of the symbol is function of the magnitude of the earthquake The thick line is axis of the trench as defined by the bathymetry Fig 4 presents the NE–SW cross-section from 36 ° N, 21 ° E to 39 ° N, 24 ° E

One of our goals was to compute reliable focal mechanisms for both shallow and intermediate earthquakes. One difficulty for crustal earthquakes arises from the strong influence of the assumed velocity structure on the positions of the observed polarities plotted on the focal sphere. In our case, the spacing between stations was about 30 km, and for shallow events upgoing rays and reliable positions on the focal sphere are rare. But for intermediate earthquakes this problem is not as critical.

The magnitudes of the earthquakes were estimated from the durations T of the coda in seconds, using the formula in the HYPO71 routine, they range from 0.4 to 4.9.

4. Results and discussion

We will comment only briefly on the results of the shallow seismicity, which will be described more thoroughly elsewhere, and here we concentrate on the seismicity deeper than 40 km.

4.1 Shallow seismicity

The shallow earthquakes are spread over a wide area (Fig. 2), and do not define clear individual faults. The highest concentration is seen in the western part of the Peloponnesus as pointed out by Leydecker et al. [21].

There are main clusters of activity: between the Gulf of Patras and the Gulf of Corinth, in the Gulf of Patras (between the Peloponnesus, Zakynthos and Kefallinia) and around 38.6 ° N, 21.7 ° E. The first cluster is well known [6,7] and is geographically related to the intersection of the 2 graben systems. But other concentrations occur in places where no recent large magnitude activity has been recorded; the cluster near 38.6 ° N, 21.7 ° E however, is located near the Lake Trikhonis where young normal faultscarps can be seen on satellite images (J. Jackson, personal communication, 1987).

Clusters are also observed along the Hellenic trench: around 37.4° N, 20.5° E; 36.7° N, 21.3° E, and 36.0° N, 22.0° E. These clusters are located where there are changes in the morphology of the Hellenic trench. One cluster (36.7° N, 21.3° E) clearly strikes NE–SW but cannot be related to any geological structure at sea with the same strike. It is located at the point where the subduction is thought to be locked [3], and also defines the boundary between the dense seismicity observed to the northwest and the lower towards the southeast.

Shallow seismicity is also observed in the region between the Peloponnesus and Crete, which is thought to be a possible seismic gap [2, 22–24]. Surprisingly, the seismicity seems to trend NE–SW, whereas all the shallow structures, beneath sea level, trend N–S [25]. Finally, no abnormal activity is observed around Kalamata (37.0° N, 22.0° E) where a destructive earthquake of magnitude 5.7 occurred 2 months later, on September 13, 1986 [17,18].

4.2 Subcrustal seismicity

One surprising result was the relatively small number of earthquakes deeper than 40 km. We located only 28 events deeper than 40 km, with most of them located better than 5 km (Fig. 3). The magnitudes of these earthquakes range from 0.5 to 4.5. Both the map (Fig. 3) and the cross-section (Fig. 4) show a deepening of the earthquakes towards the northeast. The earthquakes deeper than 40 km define a very gentle slope (about 10°) starting at the trench and continuing for 200 km, where the zone suddenly steepens to about 45°

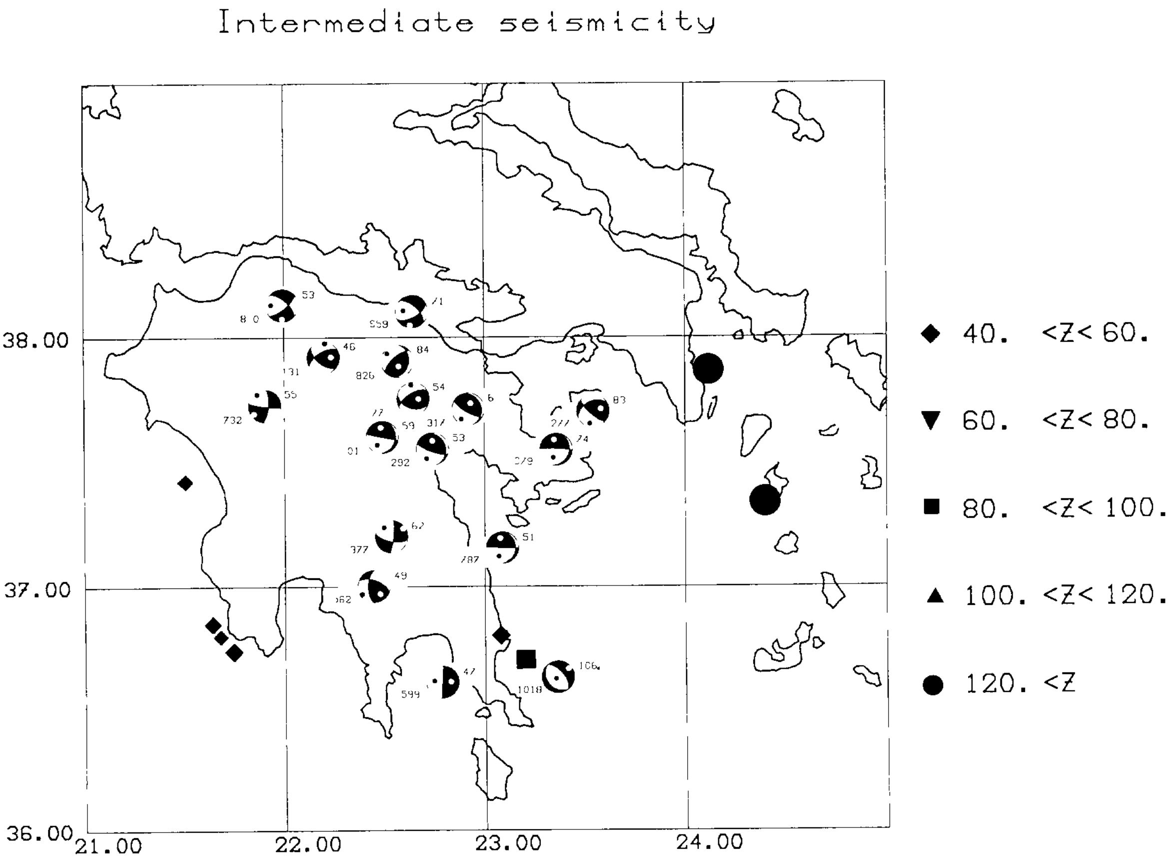

Fig. 3. Seismicity map and fault plane solutions for the subcrustal earthquakes located better than 10 km. Lower hemisphere projection with compressive quadrants shaded, lower-left number is the earthquake number, upper-right number is the depth. Notice, for the deepest events, located in the northeast, the T-axes trending north

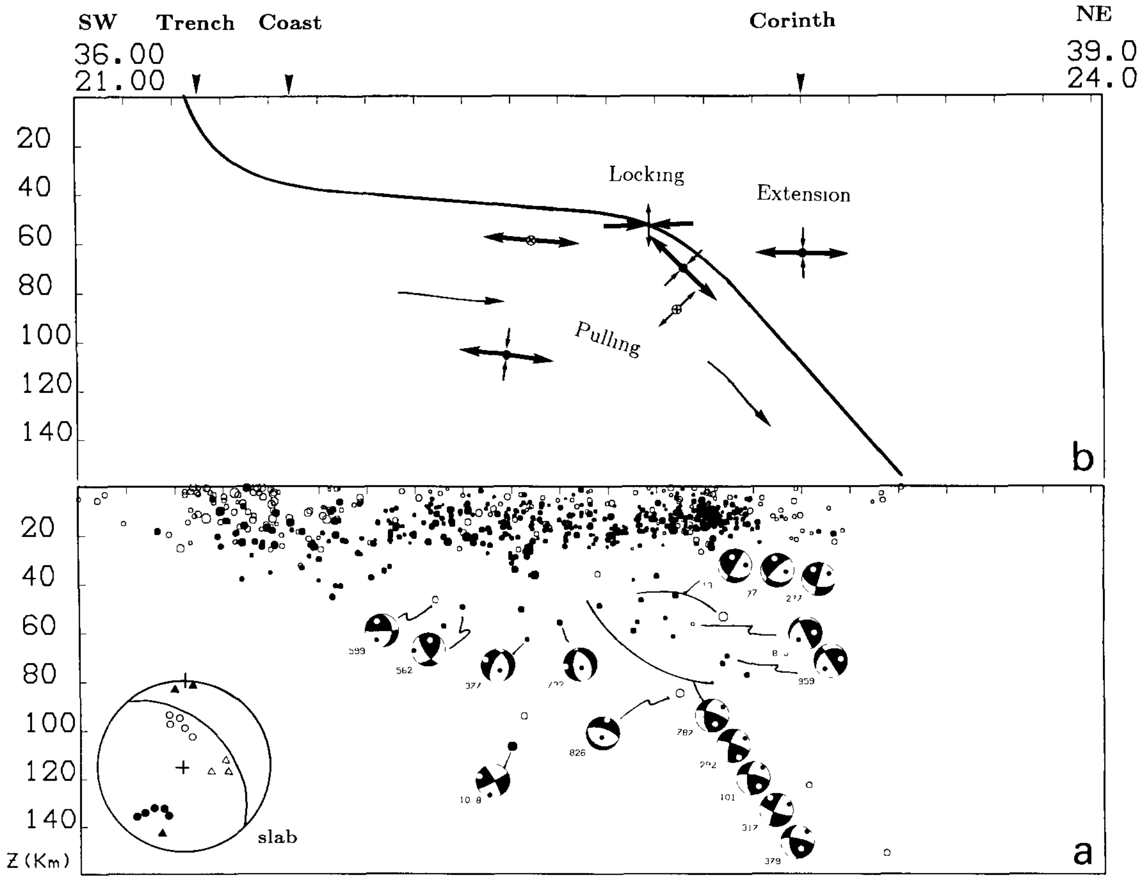

Fig. 4 Cross-section across the Peloponnesus striking NE–SW as shown in Fig. 2 (a) *Data* We observe the shallow dipping slab for the first 200 km, and a sudden dipping of the subduction beneath Argolida. Focal mechanisms are back hemisphere projection. (b) *Interpretation* We represent only the P- and T-axes, when it is perpendicular to the cross-section it is a cross within a circle We use thick arrows for the assumed main driving force Most of the focal mechanisms located within the slab show a T-axis plunging the same as the slab, there are consistent with the pulling of the subducted slab. This is also shown by the inset which represents the focal sphere with the trace of the slab, the P-axes (black symbol), the T-axes (open symbol) We observe thrust faulting where the dip changes abruptly, due to a probable locking Extension is observed down to 70 km beneath the Gulf of Corinth

beneath the gulf of Argolis. This change occurs beneath a lack of shallower seismicity within the crust.

We interpret this pattern of seismicity as occurring near the top of the subducted lithosphere, and therefore it appears that the downgoing slab is very shallow beneath a thin overriding lithosphere before it plunges more steeply into the asthenosphere. Two earthquakes (#826 and #1018 in Figs. 3 and 4), the last one with more than 50 arrival times, are located below the seismic zone and therefore within the subducted lithosphere.

The 16 available fault plane solutions for the subcrustal earthquakes are shown in Fig. 5, and listed in Table 1. The deeper part of the slab in the northeast is outside our seismological network, and so first motions do not cover the focal sphere adequately for the events deeper than 120 km. We will discuss the focal mechanisms going from north to south.

Two events (#810, 959) located beneath the Gulf of Corinth, at a depth of 50–70 km, show oblique normal faulting, with the T-axes striking N–S.

One event (#826) is located within the sub-

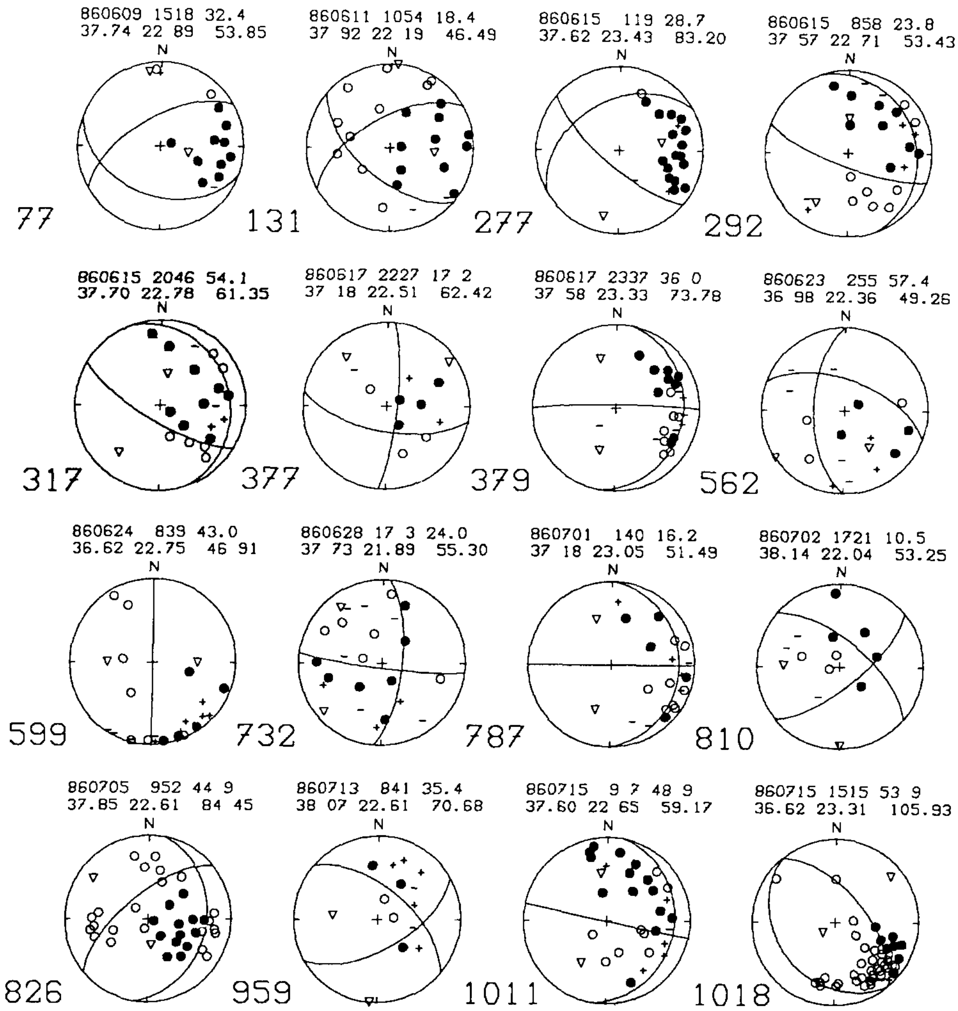

Fig 5 Lower hemisphere focal spheres of the deeper earthquakes Black and empty dots are reliable compressional and dilatational first motions, + and − are uncertain Notice the inconsistency of some readings with orthogonal nodal planes for solution #826, located within the slab.

TABLE 1
Parameters of the fault plane solutions

No	Date and time	Lat. N	Long E	Z (km)	Magnitude	Plane 1		Plane 2		P-axis		T-axis	
						az	pl	az	pl	az	pl.	az	pl
77	860609 151832	37°44 16′	22°53 45′	53	1 9	110	40	240	62	351	12	103	61
131	860611 105418	37°55 44′	22°11 32′	46	1 9	240	60	130	59	5	0	95	46
277	860615 011928	37°37 11′	23°25.99′	83	2 3	240	40	130	74	193	20	79	48
292	860615 085823	37°34 46′	22°42 33′	53	1.7	340	20	110	77	212	30	0	56
317	860615 204654	37°41.75′	22°46.60′	61	1 7	340	20	120	74	220	28	13	59
377	860617 222717	37°10 87′	22°30 48′	62	1 7	100	65	5	79	320	25	54	10
379	860617 233736	37°34.59′	23°19 90′	73	2 2	10	20	270	86	200	45	342	38
562	860623 025557	36°58.56′	22°21.44′	49	2 1	180	60	290	59	235	0	144	46
599	860624 083943	36°36 91′	22°45 21′	47	3 3	0	90	0	0	270	45	90	45
732	860628 170324	37°43 78′	21°53.57′	55	2 5	5	70	97	85	323	18	229	10
787	860701 014016	37°11 05′	23°02 90′	51	2 3	0	20	90	90	199	41	341	42
810	860702 172110	38°08 45′	22°02 43′	53	1 7	50	70	310	65	272	33	179	3
826	860705 095244	37°50 81′	22°36 48′	84	4 2	10	30	230	66	306	19	171	64
959	860713 084135	38°04 34′	22°36 39′	71	1 9	60	60	310	59	275	45	185	0
1011	860715 090748	37°36 06′	22°39 18′	59	2 4	10	20	102	89	353	42	211	41
1018	860715 151553	36°37 45′	23°18.88′	106	4 1	320	60	140	30	230	75	50	15

ducted slab (Fig. 4), we cannot draw 2 orthogonal planes for it without violating some observed polarities (Fig. 5). This is probably due to the strong velocity contrast across the boundary of the slab, dipping at 45°. Inversion of travel time data, in this area, also shows that subcrustal earthquakes are located within relatively high velocity zone [26].

Three solutions (#77, 131, 277) show reverse faulting, with the P-axis striking N–S, and the T-axis almost vertical.

Five earthquakes (# 292, 317, 379, 787, 1011) located beneath northeast Peloponnesus show a very similar pattern with an E–W striking vertical plane and the other plane almost horizontal.

Four earthquakes lcoated beneath central and southern Peloponnesus, in the shallow dipping part of the slab, show a different pattern: two (#732, 377) are strike slip motion, with the T-axes trending NE–SW; one (#599) with a N–S vertical plane and the other one horizontal; the last event (#562) shows reverse faulting, the P-axis trending NE–SW.

Finally the deepest event (#1018), 106 km deep and therefore located probably in the bottom of the subducted slab, shows normal faulting, the T-axis trending NE–SW.

It is obvious that the strain pattern is not uniform beneath the Peloponessus, for earthquakes deeper than 40 km. We have drawn an interpretative cross-section for a tentative model (Fig. 4). We do not know exactly the orientation of the slab, beneath the Peloponnesus, we chose an azimuth of 45°, which is approximately parallel to the strike of the trench.

The two normal mechanisms, close to the Gulf of Corinth, are very similar to those found for shallow strong events in the area of the Gulf of Corinth [2,15]. They support the idea that N–S extension is present within the whole lithosphere. If they seem to be mixed with the reverse mechanisms, this is due to the azimuth of the cross-section, it is clear from the map (Fig. 3) that they are not connected to the other fault plane solutions.

Concerning the three thrust focal mechanisms, they are located just above the place where the dip of the slab changes, they are pure reverse faulting, the mean azimuth is 3°E for the P-axes, and 92°E for T-axes. They can be due to the thrust of the subducted slab beneath the Aegean lithosphere.

For the five dip-slip mechanisms the mean azimuth of the T-axes is 6°W. The plunge of the T-axes, and not of the nodal planes, is the same as the plunge of the seismic zone in the steepest part (Fig. 4). It is clear that the plunge of the T-axes support the idea of a pulling of the cold lithosphere (see the inset of Fig. 4). However, the mean azimuth of the T-axes is slightly different from the relative motion of Africa relative to Aegean: 31°N according to McKenzie [2], 51–58°N according to Le Pichon and Angelier [3]. It is also different from the probable orientation of the dip of the slab. On the other hand it is very similar to the direction of the relative motion between Africa and Europe.

The four mechanisms in the flat portion of the subducted slab show a complex strain pattern, probably due to the strong coupling of the two lithospheres. Two of them clearly show horizontal T-axes trending NE–SW.

Finally two mechanisms are located within the lithosphere of the subducted slab. One (#826) is located within the upper part of the slab, beneath the place where the slab dips abruptly (Fig. 5). The T-axis is trending NW–SE and the null axis NE–SW. There is probable rotation in the principal stresses due to the bending of the slab. The other one (#1018) is located towards the trench, it shows normal faulting, with the T-axis trending NE–SW (the same as earthquakes located above), therefore it is also consistent with the pulling of the slab.

5. Conclusion

Shallow seismicity in and near the Peloponnesus is spread over a wide area, with higher concentration towards the west and occurs down to 40 km, probably both in the upper and the lower crusts. A few concentrations of activity occur, for example in the Gulf of Kefallinia or between Crete and Peloponnesus, which have not been observed before. No abnormal seismicity is observed around Kalamata where a destructive earthquake occurred 2 months after this survey. Most of the seismicity stops abruptly at about 40 km.

The deeper seismicity defines a subducted slab dipping gently (10°) towards the northeast for the first 200 km and dipping more steeply (45°) beneath the Gulf of Argolis. This result is consistent with the seismicity obtained by a careful selection of well located events by the ISC data [26].

T-axes of fault plane solutions for the deeper events are consistent with the pulling of the cold lithosphere probably towards the north. Two mechanisms, located beneath the Gulf of Corinth, at a depth of 50 km, show N–S extension, similar to the shallow earthquakes. Thus this extension is observed within the mantle and not only within the crust.

The sharp boundary between shallowly and steeply dipping subcrustal seismicity cannot be explained only by gravity pulling on the slab. If that were the case, we should observe a progressive deepening of the slab, as in other subduction zones. We think that the internal deformation of the Aegean plate near the trench, as proposed by Le Pichon and Angelier [3], and observed in paleomagnetic studies [12], modify the dynamics of the convergent boundary: part of the process is due to the loading of the subducted lithosphere by the overriding deforming plate.

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References

1 D P. McKenzie, Active tectonics of the Mediterranean region, Geophys J. R Astron. Soc 30, 109–185, 1972
2 D P. McKenzie, Active tectonics of the Alpine-Himalayan Belt the Aegean Sea and surrounding regions, Geophys. J R Astron. Soc. 55, 217–254, 1978
3 X Le Pichon and J. Angelier, The Hellenic arc and trench system: a key to the neotectonic evolution of the eastern Mediterranean area, Tectonophysics 60, 1–42, 1970.
4 J L Mercier, N Delibasis, A. Gauthier, J.J. Jarrige, F Leureille, H. Philip, M Sebrier and D Sorel, La néotectonique de l'arc égéen, Rev Géol. Dyn Géogr. Phys. 21, 67–92, 1979.
5 B Gutenberg and C F Richter, Deep-Focus earthquakes in the Mediterranean region, Geofis Pura Appl. XII, 1–4, 1948
6 B C Papazachos and P E Comninakis, Geophysical and tectonic features of the Aegean Arc, J Geophys Res. 76, 8517–8533, 1971.
7 K C Makropoulos and P W. Burton, A catalogue of seismicity in Greece and adjacent areas, Geophys. J R Astron Soc 65, 741–762, 1981
8 J Jackson and D. McKenzie, Active tectonics of the Alpine Himalayan Belt between western Turkey and Pakistan, Geophys, J R. Astron Soc. 77, 185–264, 1984
9 A R. Ritsema, The earthquake mechanisms of the Balkan region, R. Neth. Meteor Inst, Sci. Rep 74-4, 1–36, 1974.
10 J Drakopoulos and N Delibasis, The focal mechanism of earthquakes in the major area of Greece for the period 1947–1981, Seismol Lab., Univ Athens, Publ, No 2, 1982
11 B C Papazachos, A A Kiratzi, P M Hatzidimitriou and B.G Karacostas, Seismotectonic Properties of the Aegean Area that restrict valid Geodynamic Models, 2nd Wegener Conf, Dionysos, Greece, 14–16 May, 1986.
12 C Kissel, M Jamet and C Laj, Paleomagnetic evidence of Miocene and Pliocene rotational deformations of the Aegean area, Publ. Spec Geol Soc. London 17, 669–679, 1984.
13 J Jackson and D. McKenzie, Rotational mechanisms of active deformation in Greece and Iran, Publ. Spec. Geol. Soc. London 17, 743–754, 1984
14 X Le Pichon, N Lyberis, J. Angelier and V Renard, Strain distribution over the east Mediterranean ridge a synthesis incorporating new sea beam data, Tectonophysics 86, 243–274, 1982.
15 J A Jackson, J Gagnepain, G Houseman, G C P. King, P. Papadimitriou, C Soufleris and J Virieux, 1982 Seismicity, normal faulting and the geomorphological development of the Gulf of Corinth (Greece) the Corinth earthquake of February 1981, Earth Planet Sci Lett 57, 377–397, 1982.
16 J A Jackson, G.C P King and C Vita-Finzi, The neotectonics of the Aegean an alternative view, Earth Planet Sci. Lett 61, 303–318, 1982
17 B.C Papazachos, A Kiratzi, B Karacostas, D. Panagiotopoulos, E. Scordilis and D.M Mountrakis, Surface fault traces, fault plane solution and spatial distribution of the aftershocks of the September 13, 1986 Earthquake of Kalamata (southern Greece) Pageoph 126, 57–68, 1988
18 H Lyon-Caen, R. Armijo, J Drakopoulos, J Bakoutass, N Delibasis, R Gaulon, V Kostounas, J Latoussakis, K Makropoulos, P Papadimitriou, D Papanastassiou, G Pedotti, The 1986 Kalamata (south Peloponnesus) earthquake. detailed study of a normal fault and tectonic implications, J Geophys Res (in press)

19 G Pedotti, Etude sismotectonique du Péloponnèse et réponse sismique d'une vallée sédimentaire en Grèce du Nord, Thèse de l'Université Joseph Fourier, Grenoble, 1988

20 W.H K. Lee and J C. Lahr, HYPO71 (revised), a computer program for determining hypocenters, magnitude and first motion pattern of local earthquakes, U.S Geol Surv Open File Rep. 75–311, 1972.

21 G. Leydecker, H Berckhemer and N Delibasis, A study of seismicity in the Peloponnesus region by precise hypocenter determinations, in Alps, Appennines, Hellenides, Closs, Roeder and Schmidt, eds., Verlagsbuchhandlung Stuttgart, 1978

22 N N Ambraseys, On the long term seismicity of the Hellenic arc, Boll. Geof. Teor Appl XXIII, 355–359, 1981.

23 M Wyss and M. Baer, Earthquake hazard in the Hellenic arc, in Earthquake Prediction, Am Geophys. Union, Maurice Ewing Ser 4, 153–172, 1981.

24 B.C. Papazachos en P E Comninakis, Long term earthquakes prediction in the Hellenic trench arc system, Tectonophysics 86, 3–16, 1982.

25 N Lyberis, J. Angelier, E. Barrier and S Lallemant, Active deformation of a segment of arc the Strait of Kythira, Hellenic arc, Greece, Struct Geol. 4, 299–311, 1982

26 Ch. Martin, Géométrie et cinématique de la subduction égéenne, structure en vitesse et atténuation sous le Péloponnèse, Thèse de l'Université Joseph Fourier, Grenoble, 1988.