On the tectonic processes along the Hellenic Arc

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Summary. — On the grounds of existing geophysical data one might be allowed to conclude that the origin of the stress field in the Ionian center (Cephalonia-Zante-Patras) at the northwestern margin of the Aegean microplate is rather shallow and in the southeastern center (Dodecanese-Crete) is surely under the crust.

In the area occupied by the second center of higher earthquake activity the relief of the Moho-discontinuity is shallower and smoother in comparison to that derived from gravity and seismic data for the area of the northwestern center. Another difference derived from the fault-plane solutions is that the Ionian center is seated in a region of horizontal pressure; the second center in the southeastern Aegean Sea belongs to a region of paramount horizontal tension.

In the western side of the Hellenic arc the high sediment supply rate, combined with a thickening of the Earth's crust along the Ionian zone, is interpreted as evidence that accretion has occurred there until recently or may still be occurring locally; plate consumption, if any, is rather low.

The existence, on the other hand, of two very deep subparallel trenches with little fill southeast of Crete (Pliny trench, Strabo trench), combined with a very high subcrustal activity in the southeastern margin of the Aegean subplate, suggest that the subduction rate at the northern boundary of the African plate must be relatively high; no plate accretion is expected to occur there.

Riassunto. — Basandosi sui dati geofisici esistenti si potrebbe concludere che l'origine del campo di « stress » nel centro ionico (Cefalonia-Zante-Patras) al limite nord-occidentale della micropiattaforma dell'Egeo è piuttosto in superficie, e nel centro sud-orientale (Dodecaneso-Creta) è sicuramente sotto la crosta.

Nell'area occupata dal secondo centro di maggiore attività sismica il rilievo della Moho è meno profondo e meno accidentato in confronto a quello ricavato dai dati gravimetrici e sismici per l'area del centro nord-occidentale.

Un'altra differenza — tratta dalle soluzioni del piano di faglia — è che il centro ionico è situato in una zona sottoposta a pressioni orizzontali, mentre il centro nel mare Egeo sud-orientale fa parte di una zona di fortissime tensioni orizzontali.

Nella parte occidentale dell'arco ellenico l'alta velocità di apporto di sedimenti insieme ad un ispessimento della crosta terrestre lungo la zona ionica, viene interpretata come la prova che l'accrescimento si è verificato molto di recente o è ancora localmente in atto; l'erosione della piattaforma, se esiste, è piuttosto bassa.

D'altra parte, l'esistenza di due spaccature subparallele molto profonde e con piccolo apporto di materiale a sud-est di Creta (spaccatura di Pliny, spaccatura di Strabo) associata ad un'attività sub-crostale molto intensa al margine sud-orientale della piattaforma sotto l'Egeo, fa pensare che la velocità di subduzione al limite settentrionale della piattaforma africana deve essere relativamente alta. Non ci si aspetta quindi che ivi avvenga un accrescimento della piattaforma stessa.

Introduction

The complex tectonics in the eastern Mediterranean may be thought of as having been disentangled to some extent by the postulate of a number of minor plates between Europe and Africa, each in motion with respect to all adjacent plates. In the context of the plate tectonics, the tectonic zones along the southern borderlands of Europe may have been created by impingement, collision and relative motion of the postulated plates. These zones are often terminated by transform faults or rifted margins (3).

A decent number of microplates have been already identified in the Mediterranean region on the basis of the present-day seismicity at their margins. They are from west to east: the Messinian, the Adriatic, the Ionian, the Aegean, the Turkish and the Levantine subplates (Fig. 1). Le Pichon is of the opinion, that the Adriatic subplate may exist or it may be a finger of the African plate within the Eurasian plate (16).

In a section from the deep trench south of Crete to the volcanic island of Santorini, the Hellenic subduction system displays the three edgeocean typical zones: trench, arc-trench gap and arc with the Cretan ridge at the outer part of the arc-trench gap (23).

Although the present relative motion of Africa with respect to Europe is of a northward compression, the relative motion that is occurring at the southern border of Europe is not simply compressional but varies due to the interaction of the intervening microplates. Thus, as Dewey and others pointed out, the relative plate motion in the eastern

Mediterranean today is to a large extent determined not by Africa-Europe motions but by the north-south compressive motion that is occurring between the Arabian plate on the one hand and the European plate on the other. Arabia is separating from Africa along the Red Sea and the Gulf of Aden rift system. The Arabian plate, although thrusting under the Van plate along the Zagros, is pushing the Van plate north and wedging the Turkish plate westward along the north Anatolian fault (3).

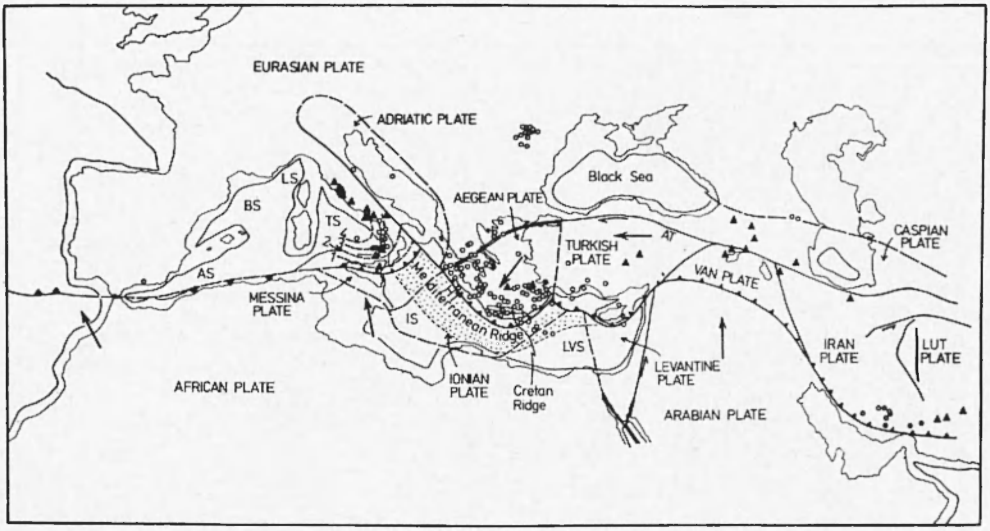

Fig. 1 – Neotectonics of the Alpine System; reproduced from Dewey and others, 1973 (Triangles = Quaternary and Holocene Volcanoes; circles = epicenters of earthquakes deeper than 100 km; arrows = slip directions of plates with respect to the Eurasian plate; dashed lines = contours on Benioff zone in hundreds of kilometers).

The Aegean subplate, due to the westward squeezing of the Turkish subplate, moves apparently to the southwest with respect to Europe, the resulting differential motion between these plates and Africa being absorbed in the Hellenic trench south of Crete. This explains, according to Le Pichon and others, the much higher seismic activity in the eastern Mediterranean than in the western Mediterranean (16). As pointed out by McKenzie, the existence of the subsidiary plates may be thought of as minimizing the work to be done in the relative movement of shortening between Eurasia and Africa (22).

SEISMOTECTONIC FEATURES

The Aegean subplate is bounded to the West and South by the Hellenic trough and two subparallel trenches, the Pliny trench and the Strabo Trench, south of Crete. The north boundary of the plate runs along the postulated westerly prolongation of the north Anatolian shear fault zone; in the context of the prolongation, it was assumed that the north Anatolian dextral shear fault system continues through

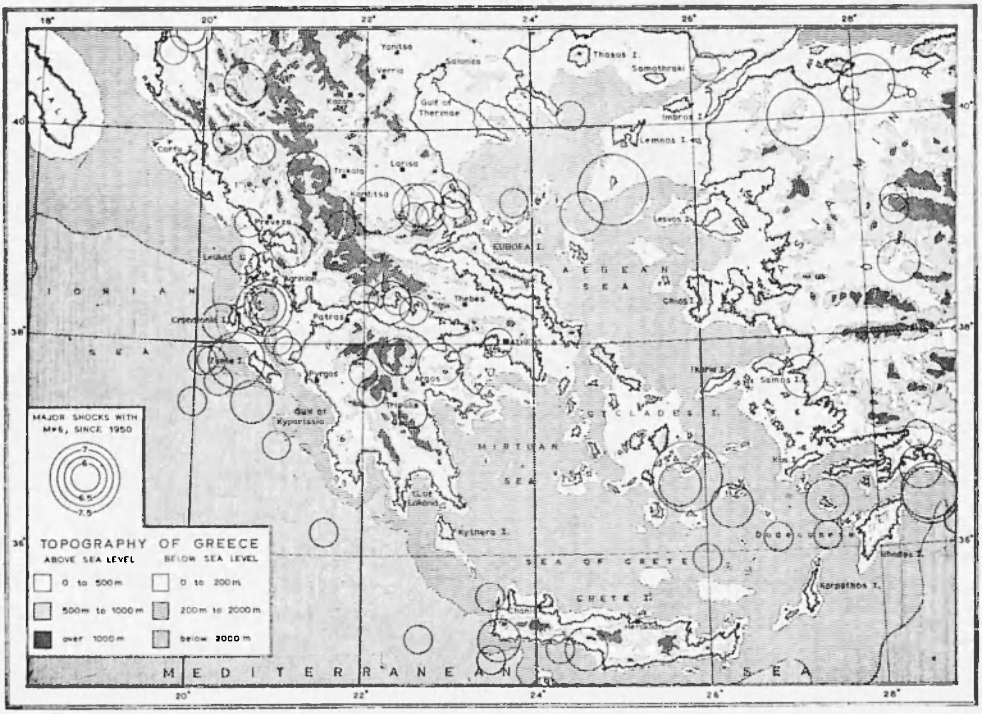

Fig. 2 – Map showing the distribution pattern of major shocks in relation to the topography of Greece.

the Trikkeri-Canal fault and some concealed, deep-seated transverse faults into the Gulf of Patras and the shear fault zone of Cephalonia-Zante (6). The lack of geological and morphological evidence for transverse faults between the Trikkeri-Canal and the Gulf of Patras (Fig. 2), and the migration of the earthquake activity from Magnesia

(Pharsala, Volos, Velestinon, 1954-1957) to the northern and northeastern Sporades (Alonisos, Skyros, St. Eustrate, 1965-1968), and in the same period to Eurytania and Acarnania (Kremasta, Katouna, 1966) and recently to the area of Leukas-Preveza (1973), favour the alternative that the Saros-Graben continues in the Trikkeri-Lamia fault zone and

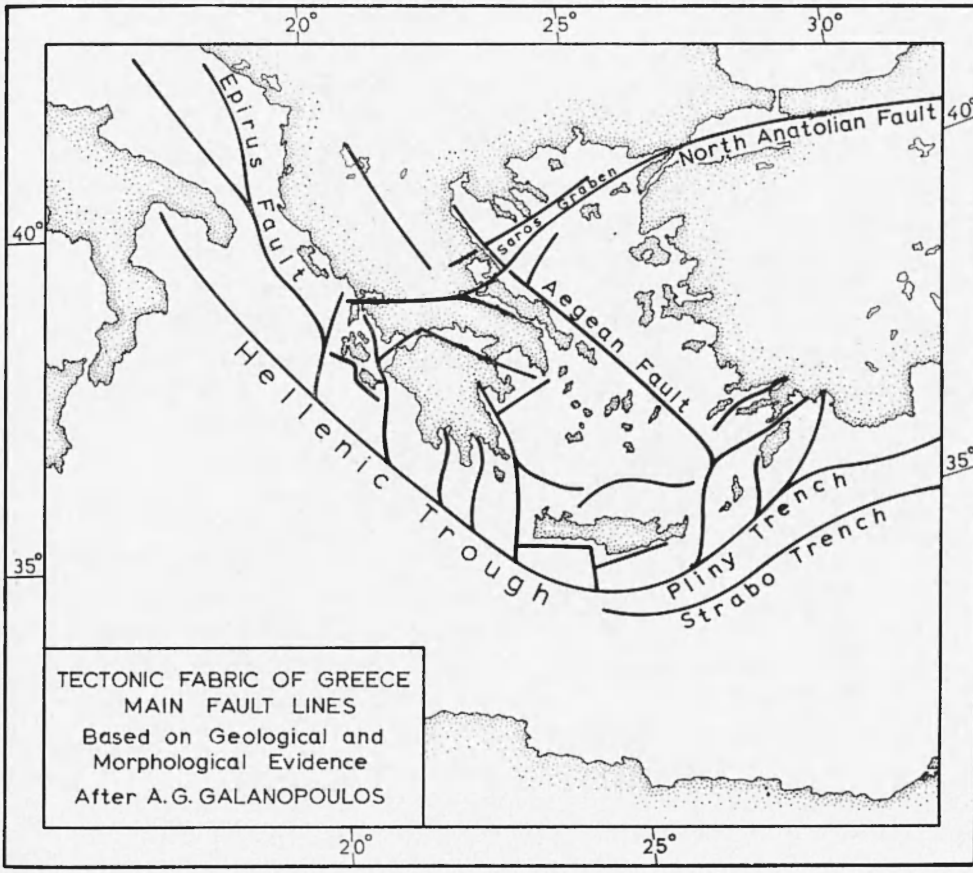

Fig. 3 – Simplified fault map of Greece.

through the northern fault escarpment of Oete mountain and the Quaternary Sperchios-Graben reaches the fault-bounded depression of the Ambrakikos Gulf (Fig. 3). The eastern boundary of the Aegean subplate is vaguely traced by a series of earthquake epicenters running from the Fethiye Gulf, between Rhodes and Kastellorizon, to the Gemlik Gulf in the Marmara Sea. The recent seismic activity in Asia Minor, 1967–1970, was seated apparently on the boundary of the Aegean and Turkish microplates (Fig. 4).

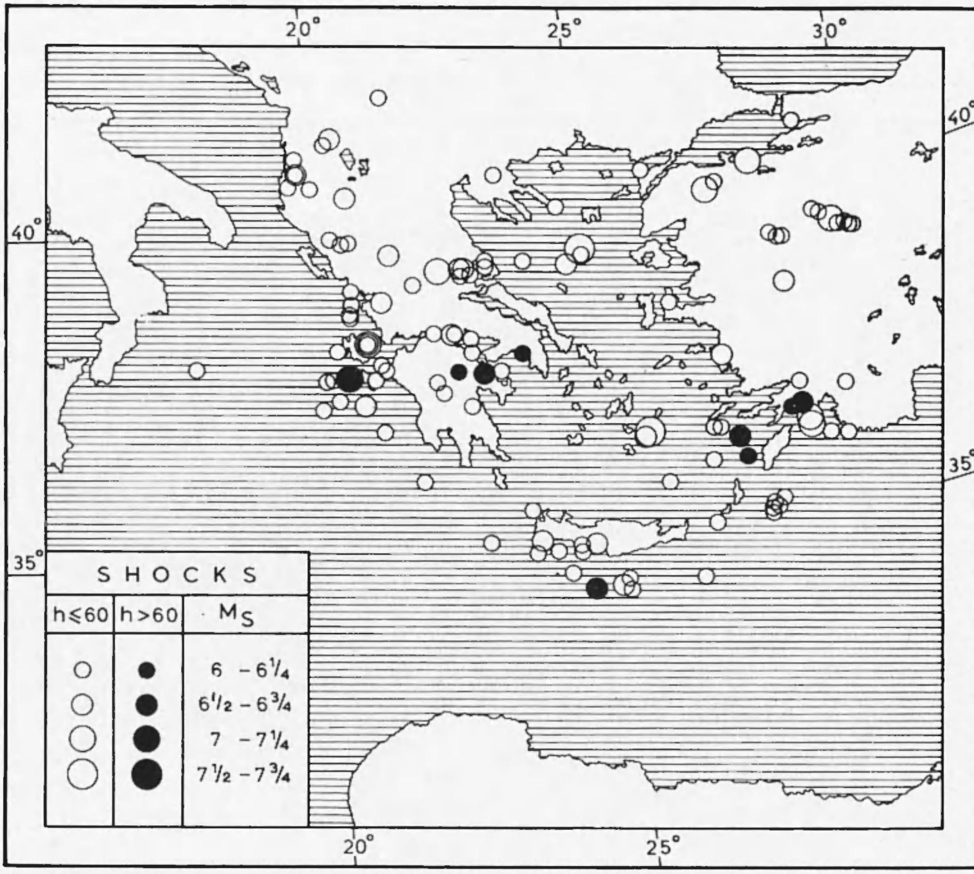

Fig. 4 – Earthquake epicenter map for the period 1950-1973.

The volcanic arc associated with the Hellenic subduction system starts from the volcanic islands of Nisyros-Yali-Kos, runs through the islands Santorini-Antiparos-Milos, it turns to the North and through Methana-Aegina-Isthmus reaches the group of the Quaternary volcanoes St. Ioannis, Likhades, Achilleion, Zileria, Thebes and Porphyrion, in the area of Lamia-Euboea-Magnesia [24]. The volcanic arc is in a roughly constant distance from the Hellenic Trough and the

Trench system that surrounds the Aegean subplate. Between the volcanic arc and the nearly parallel Hellenic Trough runs the sedimentary arc developed during the Cretaceous-Tertiary Alpine Orogeny (1). Among the Volcanoes of the Hellenic arc, Santorini, Nisyros and Methana were active in historical times; four volcanoes at the north end of the arc, among which Likhades, were active in the Holocene and probably till the end of the Neolithic age (12).

The epicenter map for the 120-years period, 1841-1960, for which the data on damaging and destructive shocks are complete (5), does not show any marked difference in the distribution pattern from the epicenter map for the 24-years period, 1950-1973, for which the parameters of the earthquakes with $M \geqslant 5\ ^1/_2$ are known with much better accuracy (Fig. 5).

In either of the epicenter maps, the boundaries of the Aegean subplate are more or less clearly delineated by earthquake foci of continuous or sporadic activity. A common feature of the epicenter maps for Greece is the continuous and relatively higher earthquake activity shown up at the northwestern and southeastern boundaries of the Aegean microplate. The two diametrically opposed centers or "poles" with maximum activity in the area of Greece are marked by a strain energy release much higher than that appeared in any other sector of the Aegean subplate or in any sector of the other subsidiary plates which presumably exist in the Mediterranean (Fig. 1).

In a general scheme, the active seismic trend of Greece is approximately double Δ-shaped, with the Δ-sides perpendicular to each other, one of them being submeridian, and the perpendicular to it running subparallel, across the Hellenic Peninsula (Fig. 5).

The first attempt to give a good reason for the clustering of the majority of the epicenters around the two "poles", the northwestern and southeastern margin of the Aegean microplate, has been strongly influenced by the relatively frequent and well documented observation of higher earthquake activity at the crosspoints of major fault zones, which generally yield to forces much easier. Biased from this principle, the concentration of the earthquake activity in the area of Cephalonia-Zante-Patras has been firstly attributed to the intersection of the Ionian fault zone with the assumed prolongation of the north Anatolian shear fault zone (6).

The second center of higher strain energy release in the area of Dodecanese-Crete is of predominantly subcrustal origin; consequently, the existence of this center can not be easily explained in terms of the above principle. The area occupied by the second center and the energy radiated from it are much higher than in the first center (9).

The Ionian center (Cephalonia-Zante-Patras) at the northwestern margin of the Aegean subplate is a site of predominantly shallow, continuous earthquake activity associated with a pronounced low of

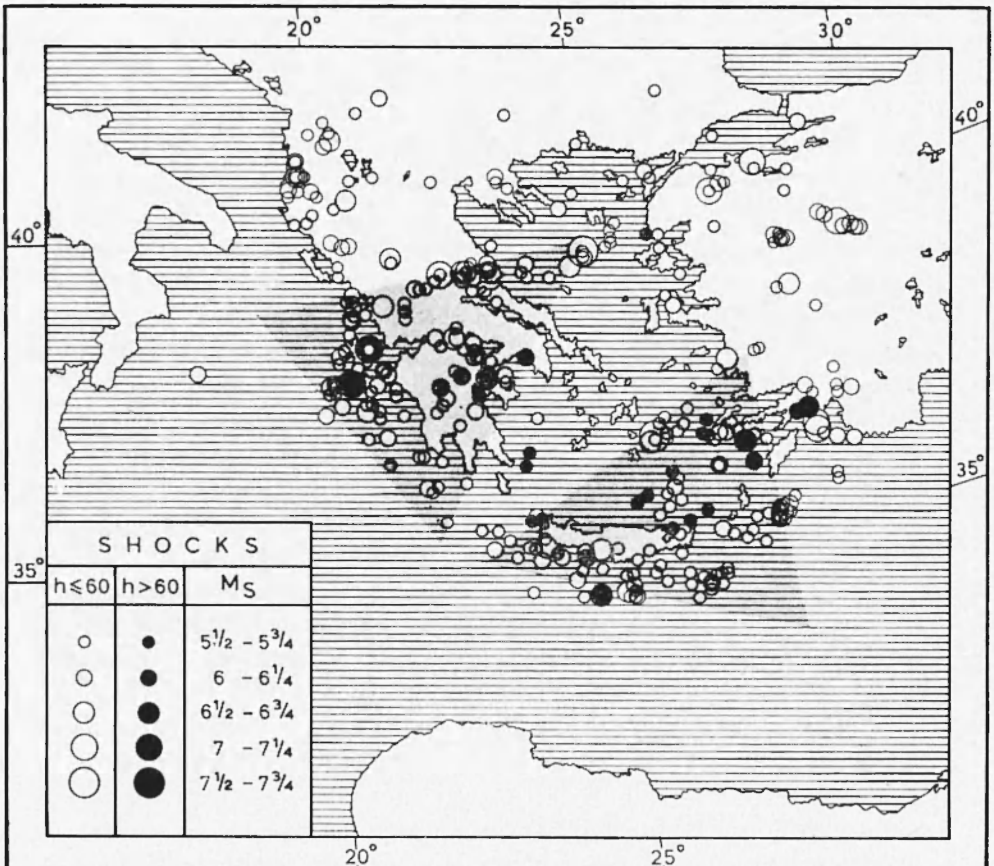

Fig. 5 – The active seismic trend of Greece, 1950-1973.

negative Bouguer anomalies (6). It is believed that due to the high sediment supply rate of a number of rivers (for example Acheloos, Peneios, Alpheios) that flow to the Ionian Sea, a plate accretion must occur in the area. In Pacific island arcs there is some evidence that accretion of crustal material occurs on the island side of the trench.

According to Lomnitz (17), the mechanisms of accretion and subduction are far from clear - cut; "accretion" as a mechanism of interaction between two plates does not necessarily involve an increase in the surface area of either plate, "since the growth can occur as a vertical thickening rather than horizontal extension of the lithosphere".

Plate consumption at the northwestern margin of the Aegean subplate, if any, is rather low. The notion is strongly supported by the lack of agreement between gravity distribution and orography; according to H. Wunderlich (26), this lack can be explained only in terms of a shifting of orogenic activity, especially of orogenic foredeeps. Wunderlich (26) believes that shifting of negative gravity anomalies is most prominent where orogenic activity continues most strongly at the present time. On the grounds of this reasoning, the *Minoides*, i.e. the Peloponnese-Crete island arc is the youngest among the various Mediterranean mountain chains and the only one still undergoing orogeny. In terms of plate tectonics, the *Minoides* is a double-arc structure with a range of folded mountains lying between the trench and the volcanoes (19).

Some years ago it was postulated that the large fault zone that surrounds the western and southern coasts of Greece marks the trend of a marginal geosyncline, which is now in the course of development in the eastern Mediterranean (5). It might be added that even in the framework of the now widely accepted concept of plate tectonics the Hellenic Trough and the Mediterranean Ridge may well be a typical pair of eugeosynclinal and miogeosynclinal structures in a "status nascendi" or embryonic stage. The trend of the Mediterranean Ridge is very poorly portrayed in the distribution pattern of earthquake epicenters; in general, the seismic activity along the Mediterranean Ridge is sparse and by far less than that occurring along the Hellenic Trough. The fact that no clear indications for horizontal compression were observed in the surveyed area of the Ionian Sea (13) is not strange for a geosynclinal couplet in process of formation (4). However, the question is still moot.

The second center of higher earthquake activity at the southeastern margin of the Aegean microplate (Dodecanese-Crete) is a place of particularly high and rather continuous, intermediate focal depth seismic activity associated with a large zone of high positive gravity anomalies (8). The lack of any river of some importance indicates that the sediment supply rate in the area is relatively very low; consequently, no plate accretion is expected to occur there. The existence, on the other hand, of two very deep, subparallel trenches with little fill southeast of Crete (Pliny trench, Strabo trench) combined with a very high subcrustal activity in the area considered, suggest that the subduction rates must be there relatively high (11).

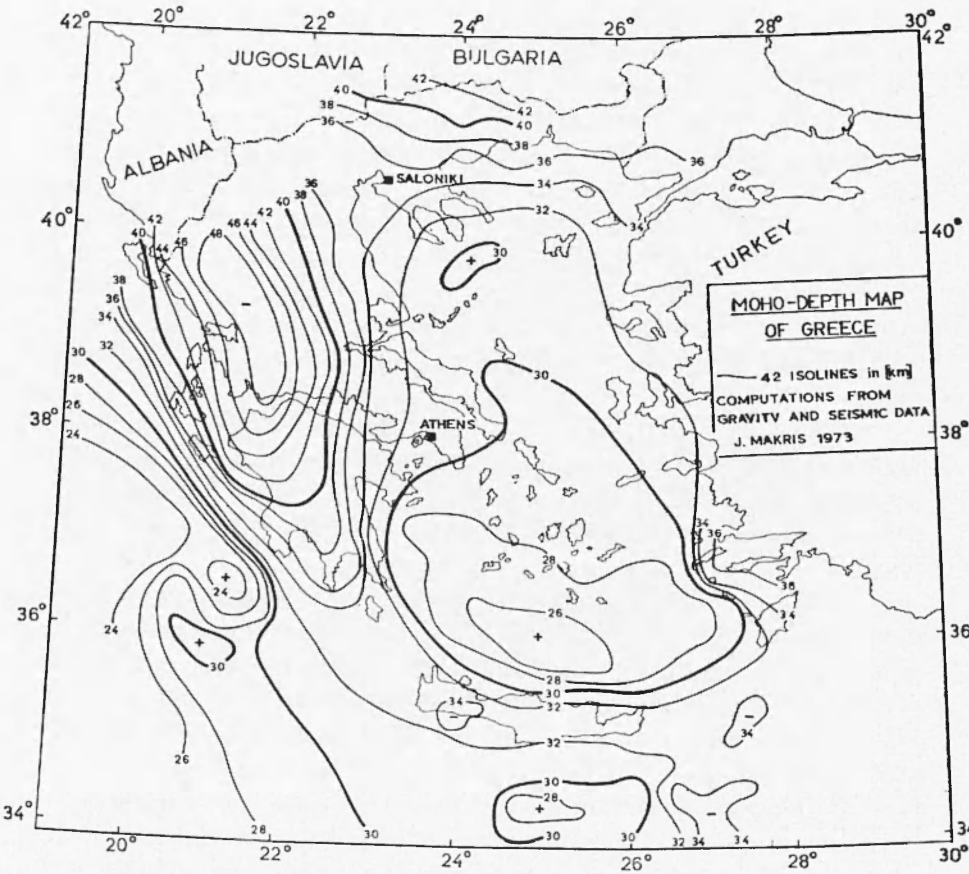

Fig. 6 – Depth contours of the Moho-discontinuity in the area of Greece, after J. Makris (1973).

Another point worth noting is that the large shock epicenters along the western segment of the Hellenic arc tend to occur near the outer or seaward side of the arc; in the southern segment there is a tendency of large shock epicenters to occur, as in most destructive plate boundaries [14], near the inner or islandward side of the arc. Plots of the large shock epicenters ($M \geq 7$) along the Hellenic arc can be found in Figures 5 and 6 of a previous work of the author [7].

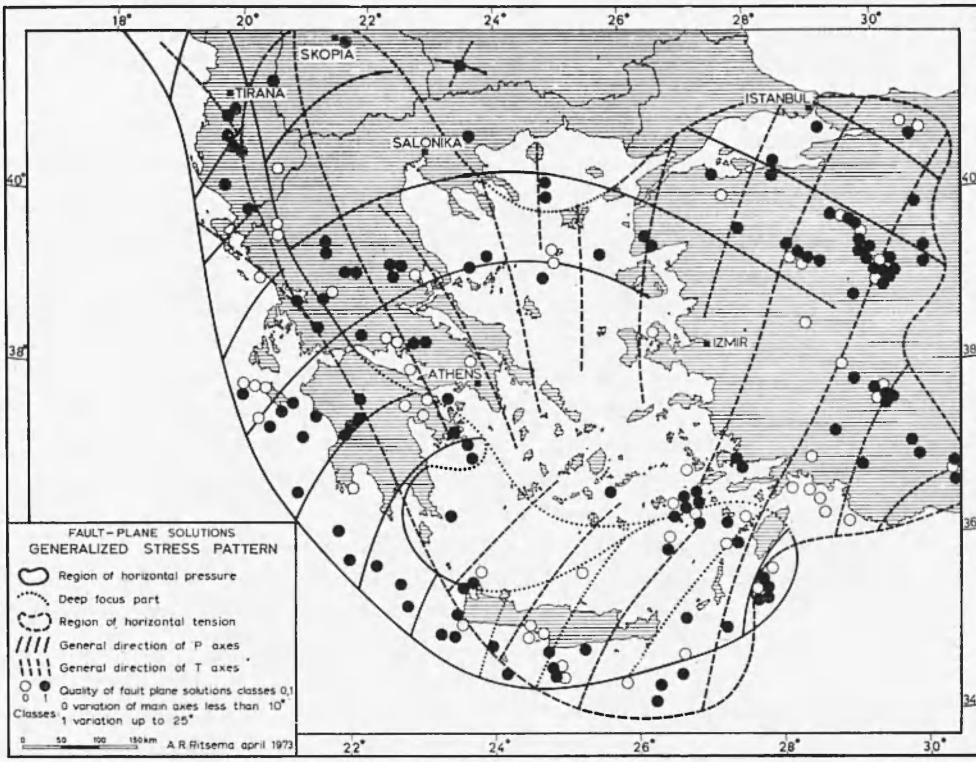

Fig. 7 – The general direction of the compressional and tensional stress in the area of Greece, after A. R. Ritsema (1974).

Discussion and remarks

On the grounds of the above considerations one might be allowed to conclude that the origin of the stress field in the northwestern center, at the constructive margin of the Aegean subplate, is rather shallow and in the southeastern center, at the destructive margin of the African plate, is surely under the crust [10].

In the area occupied by the second center of higher earthquake activity the relief of the Moho-discontinuity is shallower and smoother in comparison to that derived from gravity and seismic data for the area of the northwestern center [18]. Further, the thickening of the Earth's crust along the Ionian zone (Fig. 6) may be interpreted as Evidence that accretion has occurred there until recently or may still be occurring locally.

Another difference derived from the fault-plane solutions [25] is that the Ionian center is seated in a region of predominant horizontal pressure; the second center in the southeastern Aegean Sea belongs to a region of paramount horizontal tension (Fig. 7).

Observations by geologists who have had extensive field experience in the area of Greece have shown that since Pliocene the tectonics in the Cephalonia Island is compressional [20], and since the Mindel-Riss period tensional forces are predominant in the area of the Aegean Sea [21]. On the grounds of these and other features of the Aegean Sea, as for instance the large positive free-air gravity anomalies, the linear magnetic anomalies and the relatively thin crust, Boccaletti and associates [2] believe the Aegean Sea, particularly the Cyclades area to be an extensional back-arc basin, i.e. a marginal sea in an early development stage formed by extension and accretion due to rising magma from the mantle.

However, by and large the compressional stress field seems to be continuous throughout the region of Greece and the general northeast-southwest direction of the compressional stresses seems to be independent of the trend of the local arc structure and to be determined only by the relative motion direction of the African plate and the Anatolian or Turkish subplate. The result of these conflicting regimes is the formation of the Aegean basin by uplift and crashing of the intermediate crystalline mass and then collapsing under tension; according to A. R. Ritsema [25], the tensional stresses always seem more or less directed towards the centre of this area.

Summing up, the Dodecanese-Crete-Center at the southern side of the Hellenic arc is a subduction zone associated with tension, while the Ionian center at the western side is largely a zone of accretion related to compression; this seems to be in contradiction with the general norm of predominant stresses across convergence zones of lithospheric plates.

Assuming a N 30° E direction of the slip vector [10] and a combined speed of about 10 cm/year between the African plate and the Aegean microplate [15], the difference in the tectonic processes along the Hellenic arc might be attributed, after Xavier Le Pichon [16], to the greater speed of the two plates in the N-S direction (about 8.7, i.e. more than 6 cm/year) in comparison to that in the E-W direction (about 5, i.e. less than 6 cm/year).

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