THE AEGEAN REGION - GENERALIZED STRUCTURAL AND SEISMOGENIC PROPERTIES

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A B S T R A C T

In the present paper the 3-D P-wave velocity patterns, the morphology of the deep seismically active structures and their seismogenic properties in the Aegean region are studied. The obtained results show that different physical conditions and medium properties exist in the western and eastern part of the region. Interpretation was made on the basis of the observed surface heat flow anomalies and of the evolution of the volcanism in the Aegean region.

Ο ΧΩΡΟΣ ΤΟΥ ΑΙΓΑΙΟΥ-ΓΕΝΙΚΕΥΜΕΝΑ ΤΕΚΤΟΝΙΚΑ ΚΑΙ ΣΕΙΣΜΟΤΕΚΤΟΝΙΚΑ ΧΑΡΑΚΤΗΡΙΣΤΙΚΑ

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Π Ε Ρ Ι Λ Η Ψ Η

Οι πρόσφατες μελέτες, στα 3-D μοντέλα της ταχύτητας των κυμάτων P, στη μορφολογία της ζώνης Wadati-Benioff και στις σεισμογενείς ζώνες που ενεργοποιούνται οτα άκρα της υπερκείμενης λιθοσφαιρικής πλάκας, από την διαδικασία της βύθισης της Αφρικανικής πλάκας, καθώς επίσης και στην κατανομή ως προς το βάθος των οεισμογενών ιδιοτήτων της καταδυομένης και μη λιθοσφαιρικής πλάκας, στο χώρο του Αιγαίου, έδειξαν ότι το ανατολικό και το δυτικό τμήμα της περιοχής χαρακτηρίζονται απο διαφορετικές ιδιότητες. Στην εργασία αυτή παρουσιάζονται τα αποτελέσματα των παραπάνω μελετών. Γίνεται δε προσπάθεια να ερμηνευθούν τα αποτελέσματα με βάση τις παρατηρούμενες ανωμαλίες στις επιφανειακές θερμικές ροές και τις εξελίξεις της ηφαιστειακής δράσης στο Αιγαίο.

INTRODUCTION

The recent studies on 3-D P-wave patterns (Gobarenko et al., 1987; Christova & Nikolova, 1992), morphology of the Wadati-Benioff zone and seismically active fracture zones activated by the process of subduction in the overlying continental wedge (Vanek et al., 1987; Hanus & Vanek, 1993), and depth distribution of seismogenic properties of the sinking and overriding lithospheric plates in the Aegean region (Christova & Vanek, 1990; Christova, 1992; Christova & Nikolova, 1992) have shown that the eastern and western part of the region are characterized by different features.

In the present study the results of the above studies are generalized and an interpretation is made on the basis of observed surface heat flow anomalies and the evolution of the volcanic activity in the Aegean region.

3-D P - WAVE VELOCITY PATTERNS

The detailed investigation of the velocity structures in the Aegean region, the Eastern Mediterranean and Western Turkey is carried out by 3-D inversion of regional P-wave travel-time residuals as reported by ISC. The considered area is situated between latitudes 30^0-42^0 N and longitudes 19^0-35^0 E.

The method used is based on Backus-Gilbert formalism for linear inversion of travel times developed by Johnson and Gilbert (1982) and extended for 2-D and 3-D inhomogeneous media by Gobarenko & Yanovskaya (1983) and Yanovskaya (1984).This method permits the velocity depth pattern for a given area to be obtained using a comparatively smaller (but reliable) data set. The resolving power of the data set, the averaging kernels, as well as the error of the solution are also estimated.

The following selection criteria were adopted: considered earthquakes were of magnitude larger than 4.0 and the minimum number of stations reporting the event was set to 50; the range of epicentral distances was 6^0-15^0, i.e., the depth of penetration of the ray-path was required to be about 60-200 km. The initial data set included about 1600 individual residuals. The errors of bulletin data, due to inaccuracies in readings of the first arrivals as well as in the hypocentres location were suppressed by a statistical analysis (Gobarenko et al., 1987), which permits a set of averaged residuals along the ray-paths crossing the Aegean region and the Eastern Mediterranean to be obtained. Following the adopted procedure, a set of 112 averaged residuals was obtained.

The results of the inversion are presented in Fig. 1. The local averaged velocity corrections relative to Jeffreys-Bullen velocity model are determined at depths from 50 to 150 km at 50 km spacing. In the following, features of the velocity pattern will be considered and discussed rather qualitatively than quantitatively. This means that zones of positive, zero or negative velocity corrections will be treated as "zones of relatively velocity lows" (RVL) if their corrections are significantly lower than the corrections of the adjacent areas, the term "zones of relatively velocity highs" (RVH) will mean zones with pronounced positive velocity corrections.

The main features of the velocity patterns are as follows:
1) Three zones of RVH are observed in the studied area: the first is beneath the Sea of Marmara, the second zone stretches between the western part of Crete and Albanian coastline, the third zone is observed in the Eastern Mediterranean. The velocity corrections in the latter two zones reach values up to 0.25 km/s.
2) Two zones of RVL, through the depth range 0-150 km, are established beneath the Chalkidiki peninsula and around Rhodos, the latter being more prominent.

3) The 100-km layer is characterized by positive velocity corrections for almost the whole area in question.

It is noteworthy that the shape of RVL and RVH zones remains stable throughout the whole considered depth range.

The results obtained herein confirm the more generalized velocity patterns obtained for this region (e.g. Gobarenko et al. 1987, Ligdas et al., 1990, Drakatos & Drakopoulos, 1991, Spakman, 1991). A general coincidence of the observed peculiarities in the velocity patterns exists.

GEOMETRY OF THE DEEP STRUCTURES IN THE AEGEAN REGION

A review of the geometry of the seismically active structures in the Aegean region, i.e., the Hellenic Wadati-Benioff zone and the fracture zones, as delineated by Vanek et al. (1987) and Hanus & Vanek (1993) is presented in this section.

A block diagram which gives a general idea about the geometry of the Hellenic Wadati-Benioff zone, according to this model is demonstrated in Fig. 2,a. The Hellenic Wadati-Benioff zone is formed by two separate flanks -western (W) and eastern (E) which, due to the different dip, do not cross in depth. The W flank dips at 20^0 - 30^0 to NE and reaches a maximum depth of 180 km. The E flank dips at 40^0 to NW with a maximum depth of 170 km. An intermediate-depth aseismic gap in both flanks of the subduction zone accompanied by the occurrence of active andesitic volcanoes of the Cycladian volcanic arc was confirmed. The active volcanoes are situated directly above the gap and their products belong to the calc-alkaline suite (see Figs. 3-9, Vanek et al., 1987). The gap was interpreted as a partially melted part of the subducted slab where stress concentration cannot occur and therefore no major seismic activity is observed and, according to the authors, it may be the source of primary magma for the active calc-alkaline volcanism.

The epicentral map of events which belong to the Hellenic Wadati Benioff zone is shown in Fig. 2,b. Increased seismicity, which tends to accumulate in well-defined elongated zones in the continental wedge overlying the subduction zone is observed in the Aegean region. The zones were interpreted as deep seismically active fracture zones activated by the process of subduction (Vanek et al., 1987; Hanus & Vanek, 1993).

A comparison of the geometry of the deep seismically active structures with the outlined velocity ones (see Figs. 1,a,b,c) shows, that the W and E parts of the Wadati-Benioff zone as well as their surroundings are characterized by different velocity depth patterns. The W1 and the westernmost part of E1 of the Wadati-Benioff zone are characterized by RVH. The eastern part of E1 and the whole volume of E2 lie entirely in well pronounced RVL zone. The P-wave velocities corrections in the W flank are strongly positive and thus the velocities are higher than those in the E flank over the depth range 50-150 km. For each layer positive velocity anomalies are found for the W flank's surroundings, the velocities behind the sinking slab being higher than those infront of it. Contrast in velocities infront of and behind the E slab is not observed.

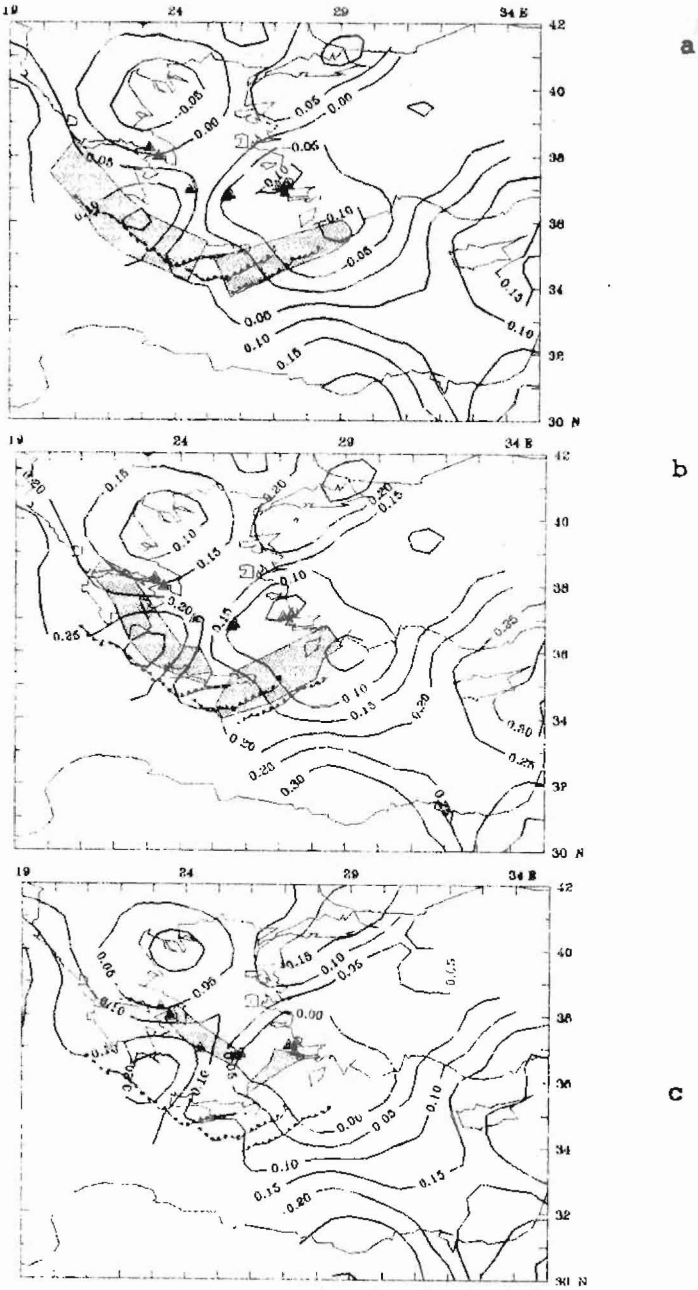

Fig.1. P-wave velocity anomalies (in km/s), relative to Jeffreys-Bullen velocity model for depts:(a)- 50 km, (b)- 100 km (c)- 150 km. The active andesitic volcanoes are denoted by full triangles; the trench axis by serrated line, the horizontal sections of the Wadati-Benioff zone at each considered depth by dotted areas.

DEPTH DISTRIBUTION OF SEISMOGENIC PROPERTIES IN THE SINKING AND OVERRIDING LITHOSPHERIC PLATES IN THE AEGEAN REGION

The ISC data from the Regional Catalogue of Earthquakes for the period 1964-82 and the earthquake catalogue for Greece and adjacent areas compiled by Makropoulos & Burton (1981) (denoted MB) for the period 1901-63 were used as data sources for studying the seismogenic properties of the seismically active structures in the Aegean region, which is roughly bounded by latitudes 33^0 and 41^0 N and by longitudes 19^0 and 30^0 E. Restrictions of the initial data were made to obtain data of comparable accuracy and homogeneity. All the ISC determinations based on observations from epicentral distances shorter than 20^0 were omitted and determinations with errors greater than 0.2^0 in the epicentral co-ordinates were rejected. Thereby, a set of ISC data has been obtained with errors in depth determinations less than ±12 km. The MB catalogue includes events with focal depth errors less than ±15 km and standard deviation of Ms ±0.3. It was tested for completeness at lower magnitudes by Step's test (Makropoulos & Burton, 1981). The Ms magnitudes of events from the MB catalogue were reduced in mb magnitudes using a regression derived by Christova & Vanek (1990). In the following, reducing Ms in mb (for events from MB catalogue), taking into account the magnitude classes with the corresponding time intervals, as compiled by the test of completeness (Makropoulos & Burton, 1981), and considering the geometry of the deep seismically active structures, samples of 831 and 569 events for the continental wedge and the Wadati-Benioff zone, respectively, were obtained.

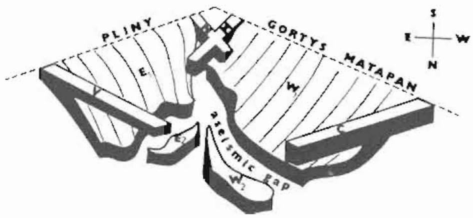

Fig.2a. Block diagram of the Hellenic Wadati-Benioff zone. E1 and W1 are the upper parts of the subduction zone, W2 and E2 are the lower parts. The active branches of the Hellenic trench system are indicated by hatched line. The fracture zones C, M, V and N have function of tectonic closures for the two flanks of the subduction zone (Vanek et al.(1987).

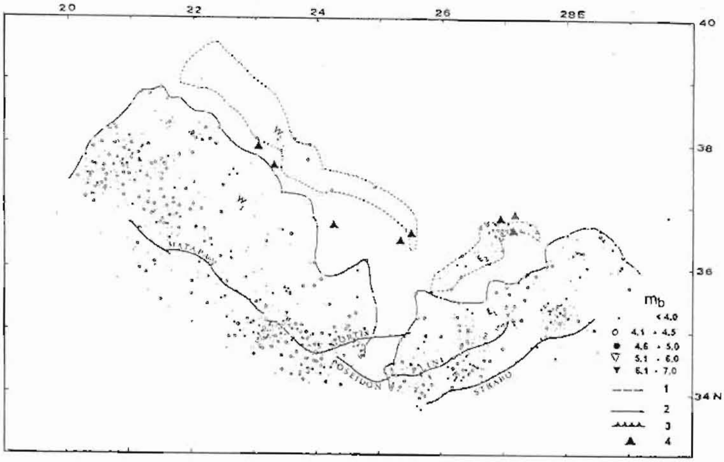

Fig.2b. Map of epicenters of earthquakes which belong to the Hellenic Wadati-Benioff zone. mb =ISC body-wave magnitude; symbols used: 1 and 2- limits of the surface projection of the lower (W2 and E2) and upper (W1 and E1) parts of the subduction zone; 3- the Hellenic trench system; 4- active andesitic volcanoes.

The depth distributions of seismic activity and energy in the W part, the E part and in the whole of the Aegean region are demonstrated in Fig. 3 a,b,c, respectively. Here N and E are the number of events and the energy (in joules) released in 50 km depth intervals overlapping at 25 km spacing. The energy of individual events was determined by generalized formula derived by Christoskov & Grigorova (1968). The method of maximum likelihood (MML) and the Page's formulae (Page, 1968) are accepted here for determining the coefficient b and the associated 95% confidence limits from the Gutenberg-Richter relation (Gutenberg & Richter, 1956). The resulting values of b for the W and E areas and for the whole Aegean region are listed in Table 1 and presented in Fig. 3. For each depth interval are given the b estimates for the Wadati-Benioff zone (WB), seismically active fracture zones in the overlying continental wedge (FZ), and for all events occurred in that depth interval (WB+FZ). Subscripts "1" and "2" refer to the upper and lower part of the subduction zone. The main features in N(h), E(h) and b(h) distributions are as follows:

1) The E1 and W1 parts of the Hellenic Wadati-Benioff zone, if considered as whole bodies, have similar seismic properties in terms of b-value, although their contributions to the total seismicity and energy of the region are different, the W1 being more seismically active. The lower parts, i.e. W2 and E2 , of the subduction zone have different seismogenic features in terms of activity, energy and b-value.

2) The W and E parts of the overlying continental wedge have

different contributions to the total seismicity, do not differ significantly in energy and differ in their b-values, which estimates are 0.86 and 0.68, respectively.

3) The N(h), E(h) and b(h) distributions in the sinking and overlying plates, as well as in the W and E parts of the region, are different. The differences in b value for W1 and E1, as well as for the W and E parts of the continental wedge are significant at depth greater than 50 km, where maxima of N were found for the two subduction flanks. The b(h) distributions within the W and E parts of the continental wedge follow the established trends within the corresponding flanks of the Wadati-Benioff zone.

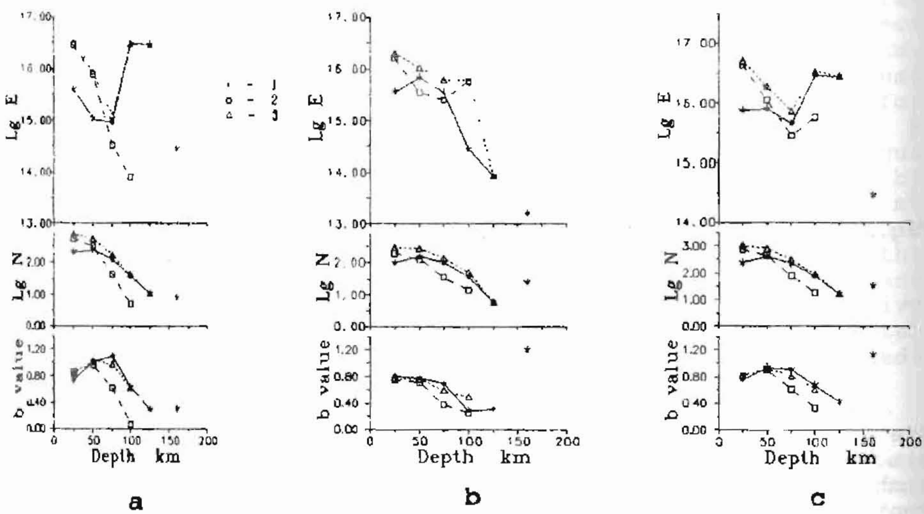

Fig.3. Depth distribution of seismic energy, number of events and b value for the Aegean region for (a) the western part, (b) t eastern part, (c) the whole region. The symbols used are as follows: 1 - for the Wadati-Benioff zone; 2 - for the overlying continental wedge; 3 - for the whole considered volume.

Studies on seismicity depth distribution in Greece and adjacent areas (e.g. Papazachos & Comninakis,1971; Bath, 1983; Papazachos & Papazachou, 1989) have shown that it decreases exponentially with increasing depth. Depth distribution of seismic energy in the Aegean region has been studied by Karnik (1967) and Bath. Bath (1983) found that, on average, seismic energy tends to decrease exponentially with increasing depth. According to Karnik (1967) the maximum of seismic energy is bound to a depth of about 100-150 km. The available reports on depth distribution of b value in Greece and in separate areas of Aegean region are discrepant. Galanopoulos (1965), Papazachos & Comninakis (1971), Karnik (1967) have observed that in Greece the b value tends to decrease with depth. In contrast, the coefficient b increases with depth over the Greek area according to Bath (1983), and in the outer part of the Hellenic arc according to Papadopoulos & Pavlides (1984). Recently, on the basis of the model of Vanek et al. (1987) the distributions of N(h) and b(h) for the Wadati-Benioff zone and fracture zones in the Aegean region were studied by Christova & Vanek (1990) and Christova (1992). These studies were extended by considering of E(h) distribution by Christova & Nikolova (1993). The results of the above studies are generalized here and will be not discussed in details. Our results differ but do not contradict the results of previous authors.

DISCUSSION AND CONCLUSIONS

It is well-known that pressure-temperature conditions of medium, and therefore its mechanical properties, determine seismological properties such as velocity of the seismic waves (e.g., Birch, 1972) and seismogenic characteristics (e.g., Gutenberg & Richter, 1956; Mogi 1962, Scholz, 1968). Scholz (1968), on the basis of experimental and theoretical studies, observed the following main tendencies in case of uniform stress field: increase in stress leads to increase in the number and energy of events and to decrease in b-value; ductile rocks have higher b-values in comparison with brittle rocks; an increase of confining pressure causes decrease in the number of event and slight increase in b-values. Scholz emphasized that the state of stress, rather than all considered parameters, plays the most important role in determining the value of b for brittle deforming rocks. According to Scholz, when nonuniform stresses are applied they will produce very high b-values.

The comparison of N(h), E(h) and b(h) graphs, as well as the data included in Table 1., and the velocity pattern show that the W and E parts of the Aegean region differ in seismogenic and velocity properties, the difference becomes clear at depth greater than 50 km. Different depth distribution of stress within the W1 and E1 parts of the subduction zone and specific rheological properties of material within E2 were assumed by Christova & Nikolova (1993) as main reasons for the observed differences in the depth distributions of the seismogenic properties. The above authors suggested that the material in the E part of the Aegean is influenced by high temperatures at present, at a depth of at least 50 km. By this suggestion they explained several phenomena: the lower seismic activity and energy of E1 part and of the E part of the continental wedge in comparison to W1 and the W part of the continental wedge; the different rheological properties of W2 and E2; the shallower by 50 km depth of the upper boundary of the aseismic gap in the E flank and, following Birch, the existence of extensive zone of RVL in the E part of the region.

The suggested heat of material in the E part of the region is examined by comparison of the anomalous heat flow pattern with a generalized velocity pattern. We suppose, that extensive heated volume corresponding to the RVL zone should be manifested in the surface heat flow pattern. A generalized scheme of the P-wave velocity anomalies (RVL and RVH) and the most prominent heat flow anomalies (Hurtig et al., 1991) in the Aegean region and adjacent areas are shown in Fig.4.

The RVH zones coincide well with the low heat flow anomalies. A similarity of the shape of RVL zones and heat flow highs is observed, but in the E part of the region the RVL zone is shifted at about 300 km southwardly relative to the former. A counterclockwise rotation of about 75^0 of RVL zone in respect to the high heat flow anomaly is observed.

Taking into account the inertia of heat transport, e.g. in highly dynamic convergent zones the estimate of time necessary for heat flow to reach its maximum is about 25-30 Ma (Smirnov & Polyak, 1977), and gradual southward decrease in the high heat flow anomaly over the E portion of the region, the shift between the RVL zone and the highest heat flow around Marmara sea might be explained by drift of a heat source and/or heated media towards the present position of RVL zone.

This means that considerable horizontal movement of cold and hot volumes (or of a heat source) could take place at least in the upper 50-150 km, during the last 30 Ma or so. The above assumption is supported by the experimental and numerical results of Olson et al. (1988). They showed that the upper mantle region becomes dynamic, i.e. horizontal and vertical transport of hot and cold volumes is possible at depth between 50 and 200 km, if pressure-temperature rheology of mantle above 450 km and heating below 450 km are considered on time scales of 10-30 Ma.

The counterclock rotation of the RVL zone relatively to the zone of maximum heat flow might be related to the westward motion of Turkey relative to Europe (e.g. Taymaz et al., 1991).

The volcanism is a phenomenon which is generally considered as reason for the observed high heat flow anomalous pattern in regions of convergent plate margins (e.g. Honda & Uyeda, 1983). A generalized scheme of the distribution of volcanic activity in the Aegean region since Oligocene times is shown in Fig. 5. The positions of the main volcanic phases since Oligocene times are according to Fytikas et al. (1984) and Papadopoulos (1989). The relative distribution of volcanic activity of different age shows a southward migration (Fytikas et al.,1984; Papadopoulos, 1989; Zeilinga de Boer, 1989). The comparison between Figs. 4 and 5 shows that the large area of high heat flow in the E part of the Aegean region covers only the central parts of the belts of Oligocene and Lower-Middle Miocene volcanic activity and the E part of the active Cycladian volcanic arc (Nisiros-Kos). In this zone the southward decrease in heat flow accompanied by decrease in the age of volcanism might be explained in the light of results by Smirnov & Polyak (1977). The maximum of heat flow around Marmara sea is probably related to the Oligocene volcanism, whereas the gradual southward decrease in the heat flow can be due to a decrease in the age of volcanism. However, the large zone of high heat flow in the eastern Aegean does not cover the whole belts of volcanic activities. This phenomenon, and the southward migration of the volcanic activity since the Oligocene, might be due to the proposed in our study migration of an external heat source and/or heated material to the south where the prominent velocity lows in the E part of the region is situated.

Table 1. N(h), E(h) and MML estimates of b with 95% confidence limits for the Hellenic Wadati-Benioff zone (WB), the fracture zones in the overlying continental plate (FZ) and the whole region under consideration (WB+FZ).

Depth range [km]		Number of shocks	Seismic energy $\times 10^{15}$ [J]	Magnitude range	b
Western part:					
	WB	202	4.010	4.3 - 6.1	0.74 ± 0.10
0- 50	FZ	554	28.400	4.3 - 6.4	0.86 ± 0.07
	WB+FZ	756	32.410	4.3 - 6.4	0.84 ± 0.06
	WB	240	1.080	4.3 - 5.9	1.01 ± 0.13
25-75	FZ	301	7.680	4.3 - 6.4	0.97 ± 0.11
	WB+FZ	541	8.760	4.3 - 6.4	1.02 ± 0.09
	WB	122	0.909	4.3 - 5.9	1.09 ± 0.19
50-100	FZ	45	0.320	4.3 - 5.6	0.62 ± 0.18
	WB+FZ	167	1.229	4.3 - 5.9	0.98 ± 0.15
	WB	38	29.200	4.3 - 6.7	0.62 ± 0.20
75-125	FZ	5	0.081	4.4 - 5.6	0.07 ± 0.06
	WB+FZ	43	29.281	4.4 - 6.7	0.62 ± 0.18
100-150	WB	11	28.500	4.3 - 6.7	0.29 ± 0.17
	WB1	335	33.300	4.3 - 6.7	0.87 ± 0.09
	WB2	8	0.275	4.3 - 5.7	0.30 ± 0.22
	WB	343	33.575	4.3 - 6.7	0.89 ± 0.09
	FZ	600	28.700	4.3 - 6.4	0.86 ± 0.07
	WB+FZ	943	62.275	4.3 - 6.7	0.89 ± 0.06
Eastern part:					
	WB	96	3.640	4.3 - 6.2	0.81 ± 0.16
0-50	FZ	191	16.010	4.3 - 6.4	0.75 ± 0.11
	WB+FZ	287	19.650	4.3 - 6.4	0.77 ± 0.09
	WB	148	6.980	4.3 - 6.2	0.78 ± 0.13
25-75	FZ	124	3.500	4.3 - 6.1	0.71 ± 0.13
	WB+FZ	272	10.480	4.3 - 6.2	0.76 ± 0.09
	WB	98	3.620	4.3 - 6.2	0.69 ± 0.14
50-100	FZ	37	2.530	4.3 - 6.2	0.38 ± 0.12
	WB+FZ	135	6.150	4.3 - 6.2	0.59 ± 0.10
	WB	37	0.277	4.3 - 5.6	0.28 ± 0.09
75-125	FZ	14	5.751	4.4 - 6.3	0.24 ± 0.13
	WB+FZ	51	6.028	4.3 - 6.3	0.49 ± 0.13
100-150	WB	6	0.086	4.3 - 5.6	0.31 ± 0.25
	WB1	200	7.340	4.3 - 6.2	0.76 ± 0.10
	WB2	26	0.016	4.3 - 5.2	1.20 ± 0.46
	WB	226	7.356	4.3 - 6.2	0.84 ± 0.11
	FZ	231	22.110	4.3 - 6.4	0.68 ± 0.09
	WB+FZ	457	29.466	4.3 - 6.4	0.75 ± 0.07
Whole region:					
	WB	298	7.650	4.3 - 6.2	0.76 ± 0.09
0-50	FZ	745	44.410	4.3 - 6.4	0.82 ± 0.06
	WB+FZ	1043	52.060	4.3 - 6.4	0.82 ± 0.05
	WB	388	8.060	4.3 - 6.2	0.94 ± 0.09
25-75	FZ	425	11.180	4.3 - 6.3	0.90 ± 0.09
	WB+FZ	813	19.240	4.3 - 6.3	0.93 ± 0.06
	WB	220	4.529	4.3 - 6.2	0.91 ± 0.12
50-100	FZ	82	2.850	4.3 - 6.2	0.61 ± 0.13
	WB+FZ	302	7.379	4.3 - 6.2	0.81 ± 0.09
	WB	75	29.477	4.3 - 6.7	0.67 ± 0.15
75-125	FZ	19	5.832	4.4 - 6.2	0.33 ± 0.15
	WB+FZ	94	35.309	4.3 - 6.7	0.61 ± 0.12
100-150	WB	17	28.586	4.3 - 6.7	0.42 ± 0.20
	WB1	535	40.640	4.3 - 6.7	0.87 ± 0.07
	WB2	34	0.297	4.3 - 5.7	1.12 ± 0.37
	WB	569	40.931	4.3 - 6.7	0.89 ± 0.07
	FZ	831	50.810	4.3 - 6.4	0.80 ± 0.05
	WB+FZ	[illegible]	91.746	4.3 - 6.7	[illegible] ± 0.04

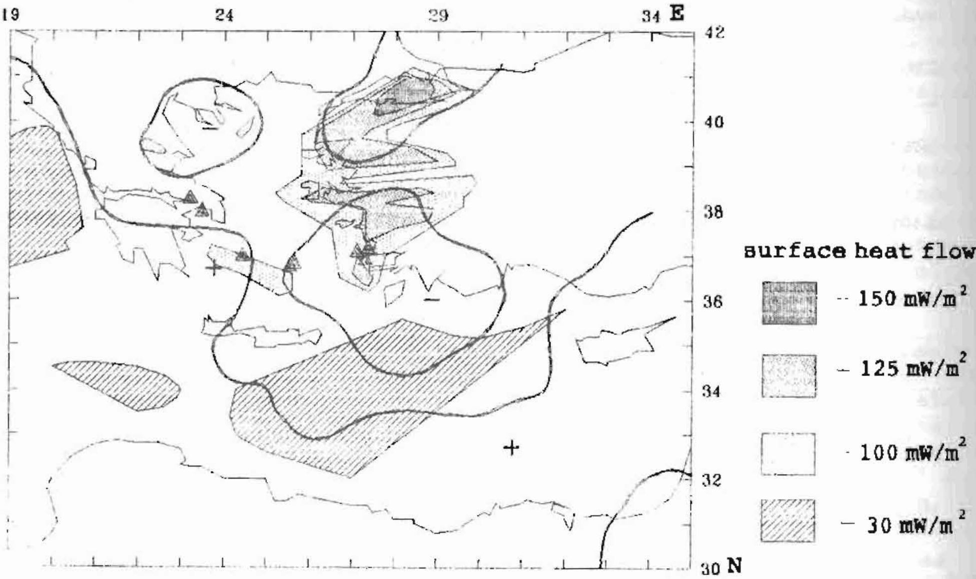

Fig.4. Generalized scheme of the surface heat flow extremes (Hurtig et al., 1991) and relative velocity anomalies. The symbols used are as follows: heavy line and "+" ("-") for RVH (RVL), filled triangles for active andesitic volcanoes.

Proposed possibilities for heating of medium in the Aegean region are existence of hot mantle plume which causes thinning of the crust below the Aegean sea (Makris, 1976), convection in the mantle wedge above the subducted slab (e.g. Papazachos & Papazacho, 1989; Papadopoulos, 1989) and gradual intrusion and uplifting of asthenolithic matter along the upper slab contact since Late-Oligocene times (Zeilinga de Boer, 1989). In these studies the high heat flow anomalies as well as the andesitic volcanism observed in the Aegean region were considered as related to the subduction processes, and as evidences for the existence of suggested mantle plume, secondary mantle convection or asthenolith. The southward migration of andesitic volcanism in the Aegean region was explained as due to southward or to southwestward migration of subduction process.

In the present study an alternative hypothesis is offerd to explain the observed RVL zones and specific seismogenic features in the E part of the Aegean region.

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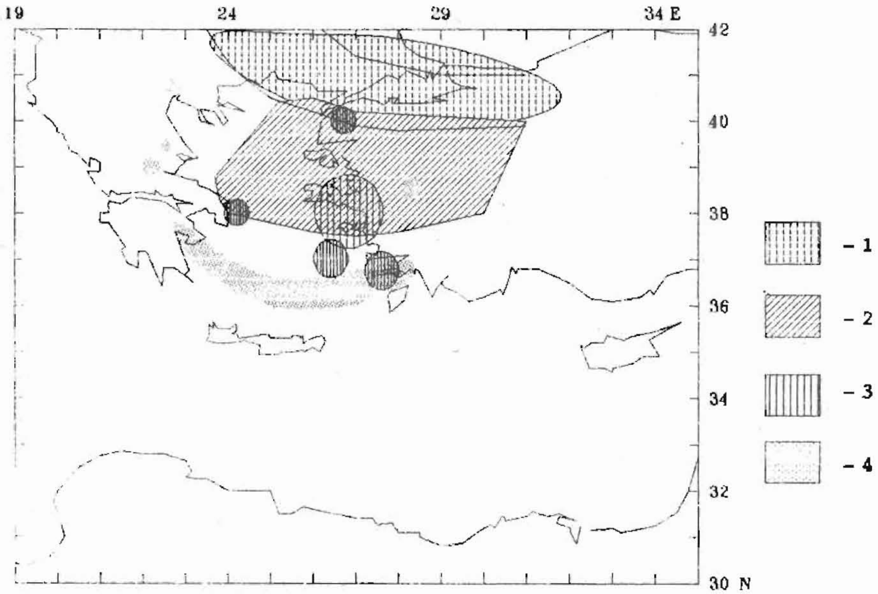

Fig.5. Generalized scheme of the relative distribution of volcanic activity in the Aegean region. The shading used are as follows: 1- Oligocene, 2- Lower-Middle Miocene, 3- Upper Miocene, 4- Pliocene-Quaternary. The scheme is compiled on the basis of the studies of Fytikas et al. (1984) and Papadopoulos (1989).

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