Tectonophysics, 124 (1986) 67–84
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

SEISMOTECTONICS OF THE AEGEAN REGION

G.A. PAPADOPOULOS [1], D.P. KONDOPOULOU [2], G.-A. LEVENTAKIS [2] and S.B. PAVLIDES [2]

[1] *Earthquake Planning and Protection Organization, 196–198 Ippokratous str., 114 71 Athens (Greece)*
[2] *Geophysical Laboratory, Geological Department, University of Thessaloniki, 54006 Thessaloniki (Greece)*

(Received February 6, 1985; revised version accepted September 17, 1985)

ABSTRACT

Papadopoulos, G.A., Kondopoulou, D.P., Leventakis, G.-A. and Pavlides, S.B., 1986. Seismotectonics of the Aegean region. *Tectonophysics*, 124: 67–84.

Fault plane solutions, neotectonic field observations, and in-situ stress measurements have been used to determine the stress field associated with the active deformation of the lithosphere in the Aegean and surrounding regions. A stress gradient and a zonal pattern of different tectonism away from the trench axis has been postulated. Pure thrust faulting occurs in the fore-arc side while the back-arc side is mainly dominated by almost N–S extensional tectonics. A narrow belt of strike-slip faults with predominantly thrust component separates these tectonic zones. This belt seems to represent a transition from the thrust-type faults to normal faults. Fault plane solutions of the whole region in question indicate that both the large and small magnitude shocks are caused by the same regional stress-field.

A body of 33 focal mechanisms indicates that the intermediate depth shocks along the sinking Mediterranean slab are associated with thrust-type fracturing. Orientation of kinematic axes favours the suggestion that shear zones within the descending slab cause these shocks. The active crustal shortening along the Hellenic consuming boundary and the sinking of the Mediterranean lithosphere beneath the South Aegean area explain satisfactorily the seismotectonic features of the fore-arc and the southern back-arc sides. On the contrary, geophysical evidence concerning the Cenozoic geodynamic evolution of the Aegean is needed to interpret features of the north back-arc area.

INTRODUCTION

It is common knowledge that the Aegean and surrounding regions constitute a highly complicated part of the Alpine–Himalayan mountain belt from a seismotectonic and geophysical point of view. For this reason, in spite of the extensive work which has been done so far in order to define their shallow and deep seismotectonic peculiarities, many points need further clarification.

The present paper is an attempt to make a contribution in this direction. Source mechanisms of shallow and intermediate depth shocks, neotectonic field observations, and in-situ stress measurements have been taken into account. Other geodynamic and geophysical observations are considered to explain the seismotectonic peculiarities of the area in question.

0040-1951/86/$03.50

TABLE 1

Information on fault plane solutions of shallow ($h < 60$ km) earthquakes with relatively large magnitudes ($M_S \geqslant 5.5$) *

Date	Origin time	ϕ_N^o	λ_E^o	M	P δ^o	P ϕ^o	T δ^o	T ϕ^o	Authors
Mar. 18, 1953	19:06:16	40.0	27.4	7.4	285	4	15	14	R
Aug. 12, "	09:23:52	38.3	20.8	7.2	66	9	215	78	M
Apr. 13, 1955	20:45:46	37.2	22.3	6.0	56	19	153	16	R
Jul. 16, "	07:07:10	37.6	27.2	6.9	260	59	353	2	M
Jul. 9, 1956	03:11:40	36.7	25.8	7.5	15	17	279	17	R
Apr. 25, 1957	02:52:08	36.5	28.6	7.2	163	25	262	19	R
Apr. 25, 1959	00:26:39	37.0	28.5	6.2	00	54	138	29	M
May 14, "	06:36:56	35.1	24.6	6.3	198	62	65	20	R
Sep. 1, "	11:37:40	40.9	19.8	6.4	260	15	121	72	R
Nov. 5, 1960	20:20:48	39.1	20.6	5.7	215	12	306	2	R
Oct. 2, 1961	07:21:44	37.0	22.0	5.7	200	35	20	55	R
Jan. 26, 1962	08:17:35	35.2	22.7	6.2	198	45	18	45	M
Mar. 18, "	15:30:30	40.7	19.6	6.0	245	33	65	57	R
Apr. 10, "	21:37:07	37.8	20.1	6.3	236	27	56	63	R
Apr. 28, "	11:18:59	36.1	26.8	5.8	140	7	50	1	R
Jul. 6, "	09:16:16	37.8	20.2	6.1	234	30	71	59	R
Jul. 26, 1963	04:17:12	42.0	21.4	6.1	234	60	342	10	R
Sep. 18, "	16:58:08	40.8	29.1	6.3	174	65	12	26	M
Dec. 16, "	13:47:53	37.0	21.0	5.9	185	34	5	55	M
Jan. 30, 1964	17:45:57	37.4	29.9	5.5	78	51	339	7	KA
Oct. 6, "	14:31:23	40.3	28.2	6.9	32	77	212	13	M
Mar. 9, 1965	17:57:54	39.3	23.8	6.1	85	00	354	00	M
Apr. 5, "	03:12:55	37.7	22.0	6.1	83	66	180	12	M
Apr. 9, "	23:57:02	35.1	24.3	6.1	150	40	42	20	DD
Apr. 27, "	14:09:06	35.6	23.5	5.7	80	72	221	14	R
Jun. 13, "	20:01:51	37.8	29.3	5.6	11	65	191	25	M
Jul. 6, "	03:18:42	38.4	22.4	6.3	00	55	175	34	M
Aug. 23, "	14:08:59	40.5	26.2	5.6	125	43	23	13	KA
Feb. 5, 1966	02:01:45	39.1	21.7	6.2	106	58	3	7	M
May 9, "	00:42:53	34.4	26.4	5.8	206	6	23	84	R
Sep. 1, "	14:22:57	37.5	22.1	5.9	266	20	168	20	R
Nov. 19, "	07:12:38	35.0	23.5	5.5	306	3	204	49	DD
Feb. 9, 1967	14:08:18	39.9	20.3	5.8	206	20	93	48	R

* Authors: R — Ritsema (1974), M — McKenzie (1972, 1978), KA — Kocaefe and Ataman (1982), DD — Drakopoulos and Delibasis (1982), P — Papazachos et al. (1984), Pa — Papadopoulos (1982).

TABLE 1 (continued)

Date	Origin time	ϕ_N^o	λ_E^o	M	P δ^o	P ϕ^o	T δ^o	T ϕ^o	Authors
Mar. 4, 1967	17:58:09	39.2	24.6	6.6	312	75	202	17	M
May 1, "	07:09:02	39.5	21.2	6.4	152	75	257	5	M
Nov. 30, "	07:23:50	41.4	20.4	6.4	115	82	244	6	R
Feb. 19, 1968	22:45:42	39.4	24.9	7.1	68	16	162	12	M
Mar. 10, "	07:10:59	39.1	24.2	5.5	32	77	170	10	DD
Mar. 28, "	01:39:59	37.8	20.9	5.9	209	22	13	67	R
May 30, "	17:40:26	35.4	27.9	5.9	200	35	10	55	M
Jul. 4, "	21:47:54	37.8	23.2	5.5	59	66	176	12	R
Oct. 31, "	03:22:14	36.6	27.0	5.7	266	16	4	28	DD
Jan. 14, 1969	23:12:06	36.1	29.2	6.2	196	28	00	60	R
Mar. 3, "	00:59:10	40.1	27.5	5.9	339	9	81	61	M
Mar. 23, "	21:08:42	39.1	28.5	6.1	261	73	359	6	M
Mar. 25, "	13:21:34	39.2	28.4	6.0	312	48	215	6	KA
Apr. 3, "	22:12:22	40.7	20.0	5.8	53	15	233	75	R
Apr. 6, "	03:49:34	38.5	26.4	5.9	26	75	206	15	M
Jun. 12, "	15:13:31	34.4	25.0	6.1	185	17	5	73	R
Jul. 8, "	08:09:13	37.5	20.3	5.9	239	45	59	45	M
Oct. 13, "	01:02:31	39.8	20.6	5.8	188	36	6	50	M
Mar. 28, 1970	21:02:23	39.2	29.5	7.1	38	79	218	11	M
Apr. 8, "	13:50:28	28.3	22.6	6.2	343	65	183	24	M
Feb. 23, 1971	19:41:23	39.6	27.3	5.5	315	4	48	30	M
May 12, "	06:25:15	37.6	29.7	6.2	333	40	142	3	M
Mar. 14, 1972	14:05:47	39.3	29.5	5.6	110	56	9	7	KA
May 4, "	21:39:57	35.1	23.6	6.5	196	39	16	47	M
Sep. 17, "	14:07:15	38.3	20.3	6.3	240	31	60	59	M
Jan. 5, 1973	05:49:18	35.8	21.9	5.6	223	14	60	75	M
Nov. 4, "	15:52:13	38.9	20.5	5.8	223	4	9	85	M
Nov. 29, "	10:57:44	35.2	23.8	6.0	229	37	49	53	M
Feb. 1, 1974	00:01:02	38.5	27.2	5.5	109	36	19	0	KA
Mar. 27, 1975	05:15:08	40.4	26.1	6.6	258	47	158	7	M
Jun. 30, "	13:26:55	38.5	21.6	5.7	237	44	62	46	DD
Dec. 21, "	16:07:51	38.5	21.7	5.5	195	69	21	21	Pa
Dec. 31, "	09:45:47	38.5	21.7	5.7	54	66	170	12	M
Sep. 11, 1977	23:19:19	34.9	23.0	6.3	230	23	111	48	DD

TABLE 1 (continued)

Date	Origin time	ϕ_N^o	λ_E^o	M	P δ°	P ϕ°	T δ°	T ϕ°	Authors
Dec. 16, 1977	07:37:29	38.4	27.2	5.5	237	62	22	25	DD
Jun. 20, 1978	20:03:21	40.8	23.2	6.5	305	76	165	10	P
Jun. 14, 1979	11:44:45	38.8	26.6	5.9	48	72	188	16	DD
Jul. 9, 1980	02:11:53	39.3	23.0	6.5	112	82	344	2	P
Feb. 24, 1981	20:53:37	38.1	22.8	6.7	315	82	191	7	P
Dec. 19, "	14:10:53	39.2	25.3	7.0	255	35	357	16	P
Jan. 18, 1982	19:27:22	39.9	24.7	6.8	106	10	207	47	P

SHALLOW SEISMOTECTONICS

The seismic activity of the Aegean region is the highest of all western Eurasia. In particular, shallow activity is very intense in that region. During the last thirty years or so, a large number of fault plane solutions of crustal ($h < 60$ km) shocks occurring in the Aegean have been published by several authors. This material is of primary importance for the comprehension of the seismotectonic behaviour of that complicated region.

One of the most common ways to study the shallow seismotectonics of a specified region is to draw maps of the stress field on the basis of fault plane solutions of crustal shocks. Table 1 supplies information on reliable fault plane solutions of 74 shallow shocks which occurred in the Aegean and adjacent regions from 1953 to 1982 and had relatively large magnitudes ($7.5 \geqslant M_s \geqslant 5.5$). These solutions have been chosen using two main criteria: (a) their good quality (accuracy, percentage of inconsistency, etc.), and (b) the coverage of as large as possible a portion of the Aegean area. The first four columns of this table include information on basic parameters of the shocks, while the next two columns give the trend, $\delta°$, and the plunge, $\phi°$, of the P (direction of maximum compression) and T (direction of maximum tension) axes. The last column gives indications for the author(s) who published the corresponding solution.

Figure 1 is a map of the stress-field associated with the shocks listed in Table 1.

Table 2 gives information on the fault plane solutions of 31 shallow shocks with smaller magnitudes ($4.8 \leqslant M_s \leqslant 5.4$). All these shocks occurred after the installation of the first Greek seismographic network (1962). The selection of the solutions is based on the same criteria as used for the selection of the solutions listed in Table 1. Nine out of 31 solutions are new. These have been graphically determined using P-wave first onsets recorded by both long and short-period instruments. The I.S.C. Bulletin has been used as data source. Take-off angles were calculated from both Hodgson-Storey (1953) tables and Ritsema (1958) curves. The number of observa-

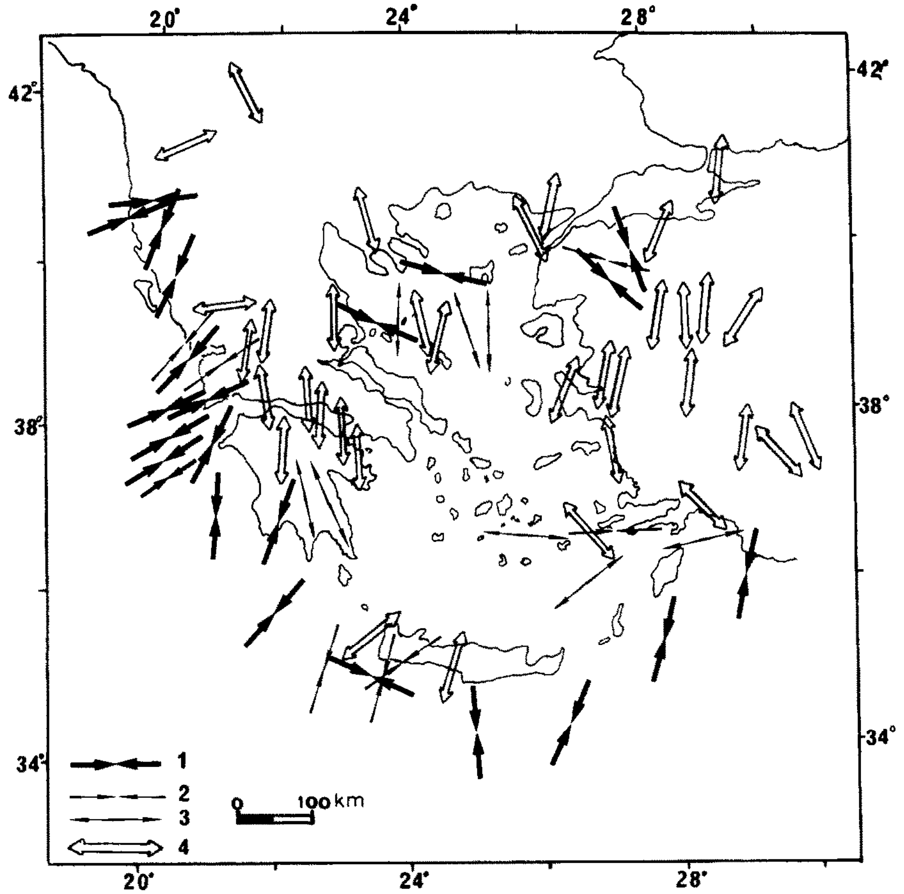

Fig. 1. Stress-field pattern related to relatively large earthquakes ($M_s \geq 5.5$). *1* = compression, *2* = strike-slip with thrust component, *3* = strike-slip with normal component, *4* = tension.

tions, n, varies between 25 and 52 with the exception of the September 29, 1974 earthquake where $n = 17$. The percentage of inconsistency fluctuates from 9% up to 19%. Figure 2 illustrates the stress field associated with the shocks listed in Table 2.

The stress-field pattern shown in Fig. 1 is in general similar to that described in previous works (Ritsema, 1974; Papazachos and Comninakis, 1977; Papadopoulos, 1982). Accordingly, the convex side of the Hellenic arc is characterized by an almost horizontal, compressive stress-field with pure thrust faulting. The mean trend of the P-axes is in about SW–NE direction. The P-axes are almost perpendicular to the arc in its northwestern part while they tend to become parallel to the arc in its southeastern part.

The concave side of the arc and the Northern Aegean are dominated by normal faults related to a tensional field oriented in an almost N–S direction. Strike-slip

TABLE 2

Information on fault plane solutions of shallow ($h < 60$ km) earthquakes with small magnitudes ($M_S < 5.5$) *

Date	Origin Time	ϕ_N^o	λ_E^o	M	P δ^o	P ϕ^o	T δ^o	T ϕ^o	Authors
Mar. 10, 1965	01:36:06	39.1	23.8	5.1	47	6	138	13	DD
Mar. 13, "	04:08:41	39.1	24.0	5.3	202	63	73	19	DD
Nov. 2, "	03:27:07	39.5	25.3	4.9	53	5	145	9	DD
Mar. 11, 1966	20:01:45	34.4	24.2	5.1	55	4	151	54	DD
May 7, "	13:08:17	37.7	27.8	5.3	173	72	353	18	R
Aug. 16, "	03:53:42	40.2	19.7	5.1	202	10	311	61	R
Jun. 1, 1967	10:39:23	36.8	29.3	5.4	22	17	118	17	R
Oct. 26, "	04:55:39	37.2	29.0	5.1	107	57	218	13	KA
Jul. 8, 1968	17:41:06	34.5	25.1	5.4	174	56	31	28	R
Aug. 15, "	02:29:43	35.2	26.7	5.2	216	57	36	33	R
Oct. 19, "	15:34:54	35.2	23.4	4.9	182	12	81	31	DD
Nov. 3, "	04:49:34	42.1	19.3	5.3	191	2	282	24	R
Nov. 3, "	18:40:02	38.8	29.1	5.0	92	35	189	10	KA
Apr. 16, 1969	23:21:06	35.2	27.7	5.4	200	35	10	55	M
Aug. 26, "	02:15:37	41.7	20.0	5.1	251	13	71	77	R
Aug. 19, 1970	02:01:52	41.1	19.8	5.4	248	24	78	65	M
Jan. 3, 1971	23:18:43	34.6	26.3	5.4	237	25	47	65	M
Apr. 26, 1972	06:30:23	39.4	26.4	5.1	106	31	200	6	M
Apr. 29, "	18:29:38	34.8	24.7	5.3	230	4	126	50	DD
Nov. 24, "	03:48:34	39.4	20.4	5.3	215	14	99	50	ns
Jan. 10, 1973	03:24:12	37.7	21.4	5.1	236	54	326	34	ns
Jan. 26, "	07:50:11	35.7	22.1	5.0	113	34	267	41	ns
Apr. 6, "	14:13:57	34.4	25.2	5.4	210	18	30	72	R
Jun. 26, "	19:05:23	34.4	26.1	5.0	206	9	111	40	DD
Oct. 14, "	18:07:06	34.7	26.3	4.9	292	9	106	73	ns
Mar. 12, 1974	18:21:35	36.8	26.4	5.0	94	4	187	4	Pa'
Jul. 9, "	02:32:15	36.6	28.5	5.3	16	3	116	1	ns
Sep. 29, "	06:35:33	35.4	27.9	4.8	228	20	110	40	ns
Jan. 3, 1975	01:59:44	35.6	27.3	5.2	126	5	221	19	ns
Jan. 9, "	18:53:44	34.8	24.0	4.8	124	26	234	23	ns
Sep. 17, "	23:04:07	36.4	23.1	5.1	240	14	110	56	ns

* Authors: DD—Drakopoulos and Delibasis (1982), R—Ritsema (1974), KA—Kocaefe and Ataman (1982), M—McKenzie (1972, 1978), Pa'—Papadopoulos (1983), ns—new solutions.

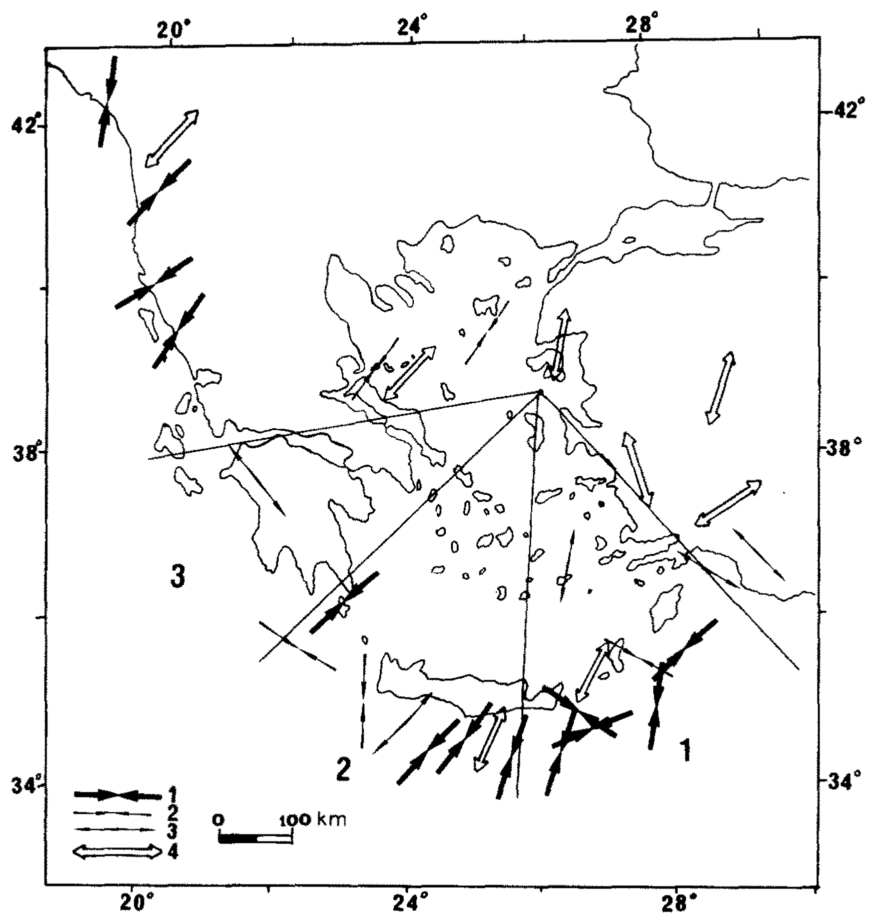

Fig. 2. Stress-field pattern related to relatively small earthquakes ($4.8 \leqslant M_s \leqslant 5.4$). Symbols are the same as in Fig. 1. The South Aegean has been divided into three equal sectors enumerated from east to west (see Fig. 4).

faulting with mainly normal components is present in the South and North Aegean Sea. However, as far as the North Aegean Sea is concerned the stress field appears to be highly complicated without a typical character. Besides the normal and strike-slip faulting there also exist pure thrusts. This reflects the tectonic complexity of that area as we shall discuss later.

Comparison between Figs. 1 and 2 shows the same picture although the latter includes a significantly lower number of observations than the former. It seems likely that both the large and small magnitude earthquakes in the Aegean area are caused by the same regional stress-field.

Other sources of information for the stresses acting in the lithosphere are neotectonic observations, in-situ stress measurements, sea-beam data, and indications from volcanic lineaments. Information of the first two kinds covers more or less the whole region under consideration. Figure 3 has been based on data concerning neotectonic observations of recent (Quaternary) or active faults, and in-situ stress measurements made by overcoring. Neotectonic observations have been compiled from a synthesis published by Mercier et al. (1979) and from other sources (Angelier, 1979; Angelier et al., 1981; Mercier, 1981; Lyberis et al., 1982a; Pavlides, 1985). Data for in-situ stress measurements are after Paquin et al. (1982, 1984). As one may observe, Fig. 3 clearly verifies the features of the stress field shown in Figs. 1 and 2.

It is of interest to note that the compressive field in the outer part of the Hellenic arc is accompanied by strike-slip faulting with predominantly thrust components.

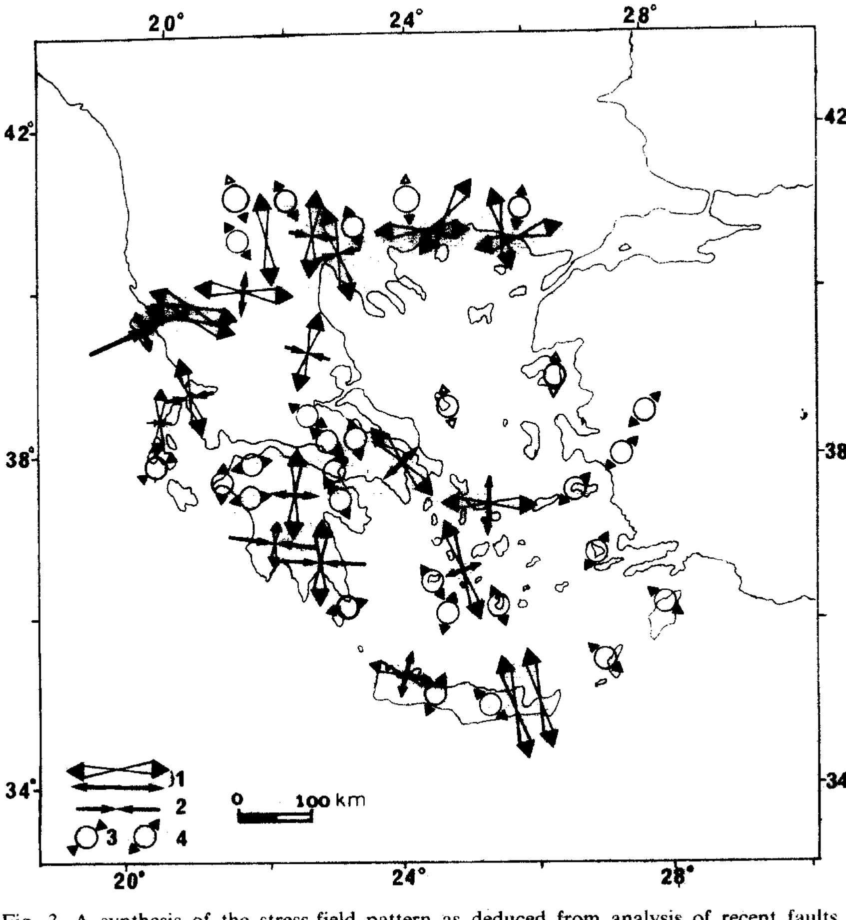

Fig. 3. A synthesis of the stress-field pattern as deduced from analysis of recent faults (neotectonic observations) and in-situ stress measurements (after sources explained in the text). Arrows and circles with small triangles indicate in-situ measurements and neotectonic observations, respectively. *1*, *4* = tension, *2*, *3* = compression.

This type of faulting can be observed in the coastal zone of the western Greek mainland (Fig. 1) and in the convex side of the arc between the meridians of 22°E and 28°E (Figs. 1 and 2). In most cases this faulting is located slightly more landward than the pure thrust zone. So, it seems that a very narrow belt of strike-slip faulting separates the two main tectonic zones in the Aegean area: the outer thrust zone and the inner extensional one. This belt separates the compressive stress-field from the tensile one, or in other words it is a transition from the thrust-type to the normal-type faults.

The conclusion from the comparison of Figs. 1, 2, and 3 is that independent methods determine the same pattern for the active (or the geologically very recent) regional stress-field in the Aegean lithosphere. In the South Aegean area sea-beam data (Lyberis et al., 1982b) and indications from volcanic lineaments (Stegena and Kolios, 1982) are in agreement with the previous pattern.

The systematic stress gradient in several regions of active or past plate convergence has been confirmed by Nakamura and Uyeda (1980). In most cases in the crust of the overlying plate the stress is, from the plate boundary landward, compressional (in the frontal zone of convergent plate boundaries), shear (often along the zone of arc volcanism), and tensional in the back-arc region. Nakamura and Uyeda (1980) believe that their zonal pattern of different tectonism applies, among others, to the Hellenic–Aegean region.

The results concerning the stress field described on the basis of Figs. 1, 2, and 3 justify, in general, this belief. However, the existence in our pattern of a narrow belt of strike-slip faulting separating the compressional zone from the tensional zone is a serious difference with respect to the stress gradient described by Nakamura and Uyeda (1980). Possible geodynamic implications will be discussed later.

DEEP SEISMOTECTONICS

The South Aegean Benioff zone

Many authors have shown (Papazachos and Comninakis, 1969, 1971; Caputo et al., 1970; Karnik, 1972; Papadopoulos, 1982) or accepted (McKenzie, 1972, 1978; Le Pichon and Angelier, 1979; Makropoulos and Burton, 1984) that a Benioff zone dips beneath the South Aegean at an angle of about 35° from SSW to NNE. This zone has a conical shape and its maximum depth is of about 190 km. Furthermore, Kondopoulou et al. (1985) taking into account only the foci of intermediate depth shocks ($h > 70$ km) found high dip values in the east and west edges of the Benioff zone (36° and 42° respectively) and low dip value in its central part (about 25°).

Papadopoulos (1983) suggested that the intermediate depth seismicity of the South Aegean tends to decrease from approximately east to west. This suggestion seems to be verified by the work of Kondopoulou et al. (1985). We independently re-examine here this point on the basis of the time variation of the strain energy

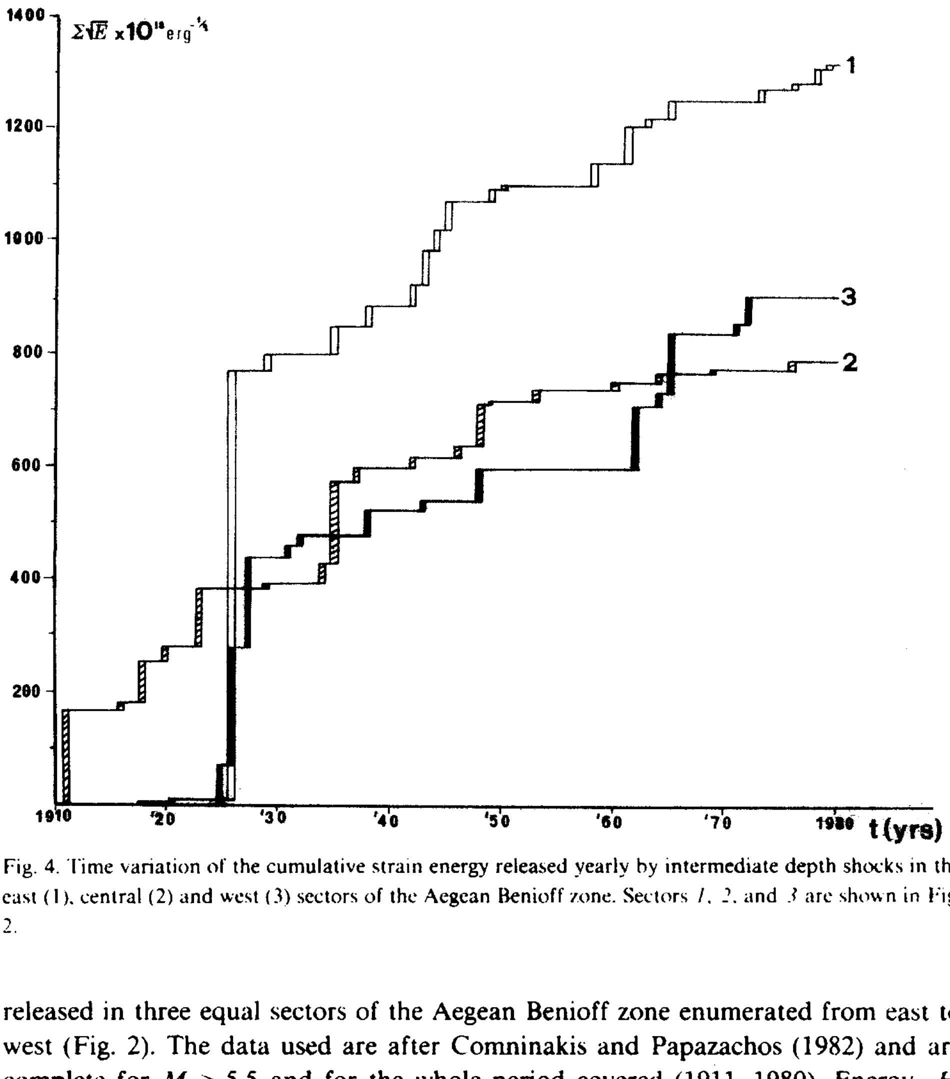

Fig. 4. Time variation of the cumulative strain energy released yearly by intermediate depth shocks in the east (1), central (2) and west (3) sectors of the Aegean Benioff zone. Sectors *1*, *2*, and *3* are shown in Fig. 2.

released in three equal sectors of the Aegean Benioff zone enumerated from east to west (Fig. 2). The data used are after Comninakis and Papazachos (1982) and are complete for $M_s \geqslant 5.5$ and for the whole period covered (1911–1980). Energy, E, liberated by one particular shock has been computed from the formula (Båth, 1973):

$$\log E = 12.24 + 1.44 M_s \tag{1}$$

Figure 4 clearly shows that the energy released in the sector 1 (southeastern part of the Benioff zone) is significantly higher than that released in the sectors 2 and 3 (central and northwestern parts of the Benioff zone, respectively). A large amount of energy in the sector 1 was contributed by the great $M_s = 8.0$ earthquake of June 26, 1926 which is the largest shock which occurred in the Aegean and the adjacent regions during the present century. Assuming that Aegean intermediate depth shocks with a magnitude of that order have large return periods, and that such shocks incidentally did not occur in the sectors 2 and 3 during 1911–1980, then, Fig. 4 may represent an artificial picture. Historical data (Papazachos and Comninakis, 1982) indicate that during the 19th century at least seven intermediate shocks with magnitudes ranging from 7.0 up to 8.3 occurred in the Hellenic arc. The three largest of them ($M_s = 8.3$, 7.8, 7.5) occurred in the region of sector 1 while the rest took place in the sectors 2 and 3. Hence, it is very probable that Fig. 4 shows a real difference between sector 1 and sectors 2 and 3.

The tendency of the seismicity to decrease from east to west is difficult to be explained; this may be related to the difference in the lithospheric convergence rate, r, between the east ($r = 4.5$ cm/yr) and the west ($r = 2$ cm/yr) part of the Hellenic arc (Le Pichon and Angelier, 1979). However, this explanation must be considered as hypothetical and, for this reason, it needs further elaboration.

Focal mechanism

Focal mechanisms of intermediate depth shocks in the South Aegean have been published by several authors. Very recently, Kondopoulou and her colleagues (1985) compiled 33 reliable solutions 17 of which have been presented by other researchers and the remaining 16 being new solutions. Examination of these solutions determined by the method of first P-wave onset, showed that intermediate depth shocks in the South Aegean as a rule are of the thrust type. The mean trend of P-axes is found to be about S230°W.

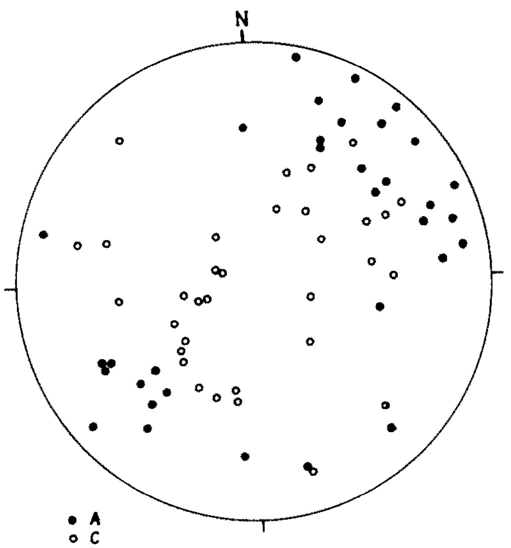

Fig. 5. Plots on an equal area projection of A- and C-axes of the focal mechanism of 33 intermediate depth shocks. A-axes (slip-vectors) have a general northeast trend.

The plot of A- and C-axes of that 33 solutions on a stereographic projection of the focal sphere is shown in Fig. 5; A and C being the slip direction on the fault plane and the axis normal to the fault plane. According to the method based on the first P-wave motion, we can determine the direction of all kinematic axes. However, it is impossible to distinguish between A and C-axes, that is to say between fault plane and auxiliary plane (plane on which axis C lies).

Let us consider that between A- and C-axes, the A-axis is that which has the smaller plunge. In this case the mean trend of A-axes, which is found to be N52° ± 26°E, is in good agreement with the direction of plate convergence. Most of the A axes (21 out of 33) plunge to approximately northeast while the remaining 12 plunge to southwest. For this reason, the mean plunge which is almost horizontal, does not agree with the dip angle of the Benioff zone (~ 35°). However, it is reasonable to suggest that the A-axes (slip directions or slip vectors on the fault plane) are these which dip to the inner (northeast) side of the arc and not necessarily those with the smaller plunge. Papazachos (1977) used some solutions published earlier by Ritsema (1974) and presented evidence that the A-axes represent the real slip directions along the Benioff zone. If this is the case, the mean plunge of A-axes becomes 30° NE approximately and is in very good agreement with the dip angle of the Benioff zone. Now, the mean trend of A-axes is being N64° ± 44°E.

On the basis of the above mentioned 33 focal mechanisms as well as the fault plane solutions of shallow shocks listed in Tables 1 and 2, we developed a model which explains the main, shallow and deep seismotectonic features of the South Aegean area (Fig. 6). Considering as nodal planes those with the smaller dip angle (Papazachos et al., 1984), we can see that normal faults related to shallow shocks in the South Aegean seismogenic layer dip either to approximately north or to south. Because of this and of the relatively small number of solutions, the representation in the model of these faults and of the associated stress-field is indicative. In general, the dip angle of these faults is of the order of 15°.

The mean plunge of P- (compressional) and T- (tensional) axes has been computed for four focal depth ranges in the sinking lithosphere. The mean plunge of P-axes in depth $h < 60$ km is 16° ± 13°SW, while the mean plunge in the depth ranges of 60–79 km, 80–119 km, and 120–160 km was found to be equal to 6° ± 17°SW, 3° ± 16°SW, and 16° ± 27°SW respectively. This indicates that the P-axes in the sinking lithosphere are almost horizontal and dip to SW, that is to the direction of the Mediterranean Sea; T-axes are almost vertical. The P-axes make an angle of about 25°–30° with the dip direction of the slab.

It is generally known (e.g. Bott, 1982) that in a homogeneous and isotropic substance the two complementary planes of fracture subtend each an angle of less than 45° to the maximum principal pressure (characteristically about 30°). According to the Coulomb-Navier hypothesis of shear fracture, the reason for this angle being less than 45° is the influence of internal friction on the attitude of fracture planes. Thus, in our case this favours the suggestion (Papazachos, 1977) that the

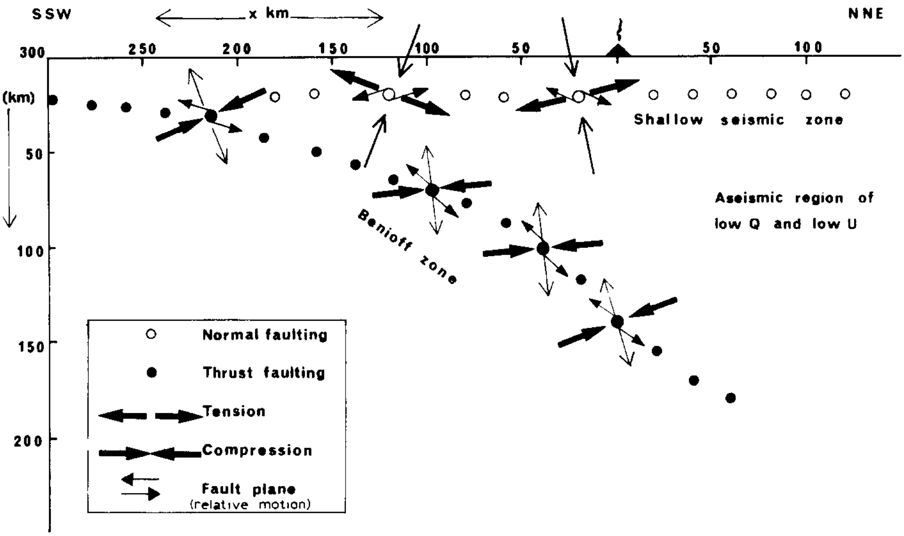

Fig. 6. Seismotectonic model of the South Aegean region which completes previous lithospheric ones (Papazachos, 1977).

A-axes show the dip direction of the slab and that shear zones within the descending slab may be responsible for the cause of intermediate depth shocks in the Hellenic arc. Such shear zones are attributed to the tendency of the colder portions of the slab to sink and the warmer portions to rise (Toksöz et al., 1971).

Isacks and Molnar (1969, 1971) found that in the uncontorted parts of deep earthquake belts either the maximum or the minimum compression is oriented parallel to the dip of the belt whereas the intermediate direction is horizontal and parallel to the strike of the belt. They suggested that the intermediate and deep focus eartquakes are predominantly caused by the release of stress within the sinking plate of lithosphere rather than by shearing at its upper boundary. According to Hasegawa et al. (1978) the focal depth distribution of small earthquakes in the northern Honshu region (Japan) shows the existence of a double-planed Benioff zone, the lower plane lying 30–40 km below the upper one. The earthquakes of the upper plane show downdip compression or reverse faulting and those of the lower plane show predominantly downdip extension. Bott (1982) suggested that a possible explanation for the different state of stress in the upper and lower planes of the double earthquake belt beneath northeastern Japan is that the upper belt represents shear motion and the lower belt is caused by downdip tension related to the downpull of the slab.

Thrusts associated with shallow ($h < 60$ km) earthquakes in the lithosphere of the outer part of the Hellenic arc can be attributed to the compressional stresses acting at the plate interface. Some of the thrusts within the 60–79 km depth range may also be caused by the direct lithospheric interaction.

Figures 1 and 2 clearly show that extensional stresses exist in the shallow seismogenic layer of the Crete island region. It is not known so far whether these stresses are associated with earthquakes occurring in the Aegean or the Mediterranean lithosphere. If we assume the first possibility, then, it is very difficult to give a reasonable geodynamic interpretation. On the contrary, the existence of these stresses can be readily explained suggesting that they are acting in the seaward upper portion of the subducting plate and are caused by the bending down of this same plate. A similar state of stresses has been recognized in other subduction zones and analogous interpretation has been given (e.g. Uyeda, 1983).

A relatively narrow belt of strike-slip faulting strikes from about east to west in the South Aegean area covering a part of the volcanic arc region. The magnitude $M_s = 7.5$ Amorgos earthquake of July 9, 1956, which is the largest shallow shock reported in Greece during the present century, as well as the magnitude $M_s = 7.2$ earthquake of April 25, 1957 are associated with this belt. The tectonic origin of the belt in question is not well documented. It has been suggested (Papadopoulos, 1983) that this belt is a tectonic boundary along which shear motion takes place between the two lithospheric segments located north (Central Aegean segment) and south (South Aegean segment) of the boundary. The main cause of this motion probably is the movement of the central Aegean segment from approximately NNE to SSW as a consequence of the tensional field in the Aegean Sea.

DISCUSSION

The proposed model explains the predominant seismotectonic features of the outer part of the Hellenic arc and of the South Aegean. It is understood that the main cause of these features may be the active convergence between the Aegean and the Mediterranean lithosphere and the subduction of the latter beneath the former. The convergence process creates compressions and thrusts in the convex side of the arc, while shear zones within the sinking slab probably produce the seismic faulting along it. Secondary convection currents in the asthenospheric wedge and hot material intrusion in the South Aegean crust, according to the McKenzie (1969)–Sleep and Toksöz (1973) mechanism, may cause its extensional tectonics. A question arises, however, about the origin of the narrow belt of strike-slip faulting which separates the compressional stress from the tensional one. These strike-slip faults have as a rule a thrust component. This implies that a shear motion may take place between the Mediterranean and the Aegean lithosphere along this narrow belt. According to Le Pichon and Angelier (1979), a counter-clockwise rotation of about 30° of the Hellenic consuming boundary, in respect to the Eastern Mediterranean Sea floor, took place during the last 13.5 m.y. This point of view is reinforced by the work of Papadopoulos (1984) on the basis of independent observations. If this also holds for the present consuming boundary, as the last mentioned suggested, then, that strike-slip faulting with thrust component could be attributed to shears occurring at the Mediterranean–Aegean lithospheric interface.

Seismotectonic peculiarities of the North Aegean are not easily explained by that model. The main difficulty comes from the fact that the McKenzie–Sleep–Toksöz mechanism is not applicable in this case because the maximum bending of the subducted slab is strictly limited beneath the active volcanic arc of the South Aegean. Thus, two main questions must be answered; the first concerns the origin of the extensional tectonics which prevails in the whole Central–North Aegean, while the second question is focused on the origin of the compressional forces in the North Aegean Sea.

Geophysical peculiarities of the North Aegean area, such as high heat flow and geothermal manifestations, magnetic anomalies, Tertiary and Plio-Quaternary volcanism, indicate that these questions could be answered in the light of the geodynamic evolution of the Aegean region during the Cenozoic. Papadopoulos (1984) elaborated about 1200 whole rock chemical analyses of Cenozoic magmatic rocks of the Aegean region, reviewed the geophysical features of this region, and suggested a model for its Cenozoic geodynamic evolution. According to this model, four successive, distinct in space and time phases of lithospheric subduction took place in the Aegean area, the last of them being currently active in the Hellenic arc. Metallogenic evidence supports this suggestion (Papadopoulos and Andrinopoulos, 1984). The idea that at least one Tertiary lithospheric subduction occurred in the North Aegean is demonstrated by Boccaletti et al. (1974) and Papazachos and Papadopoulos (1977). The two last mentioned suggested that such a zone is currently dying off, but it is still weakly active and causes the compressional field in the North Aegean Sea.

The process of successive crustal shortening during the Cenozoic is attributed to the successive sinking of lithospheric blocks-remnants of the Tethyan ocean which subducted beneath the southern front of the Eurasian plate (Papadopoulos, 1984). These blocks were probably counter-clockwise rotated while the Aegean lithosphere was clockwise rotated. These findings, based on observations concerning the temporal and spatial distribution of the Cenozoic magmatism in the Aegean area as well as its petrochemistry, are in agreement with the model of Le Pichon and Angelier (1979) above mentioned. Palaeomagnetic evidence gives also support to this suggestion. Figure 7 illustrates palaeomagnetic directions (mean declination) observed in Cenozoic formations of the Aegean (after Lauer, 1981; Kondopoulou, 1982; Laj et al., 1982; Horner and Freeman, 1983; Kissel et al., 1984, 1985; Kondopoulou and Westphal, 1985). From this figure it follows that the clockwise rotation of the Aegean area during the Tertiary is a possible fact.

In any case, the process of Tertiary lithospheric consumption may have induced currents which must be still active as the geophysical peculiarities mentioned earlier imply. These currents could be considered as responsible for the present tensional field of the Central and North Aegean area. It is noteworthy that other authors, among which Makris (1976) and McKenzie (1978), speak also for intrusion of hot material beneath the Aegean Sea.

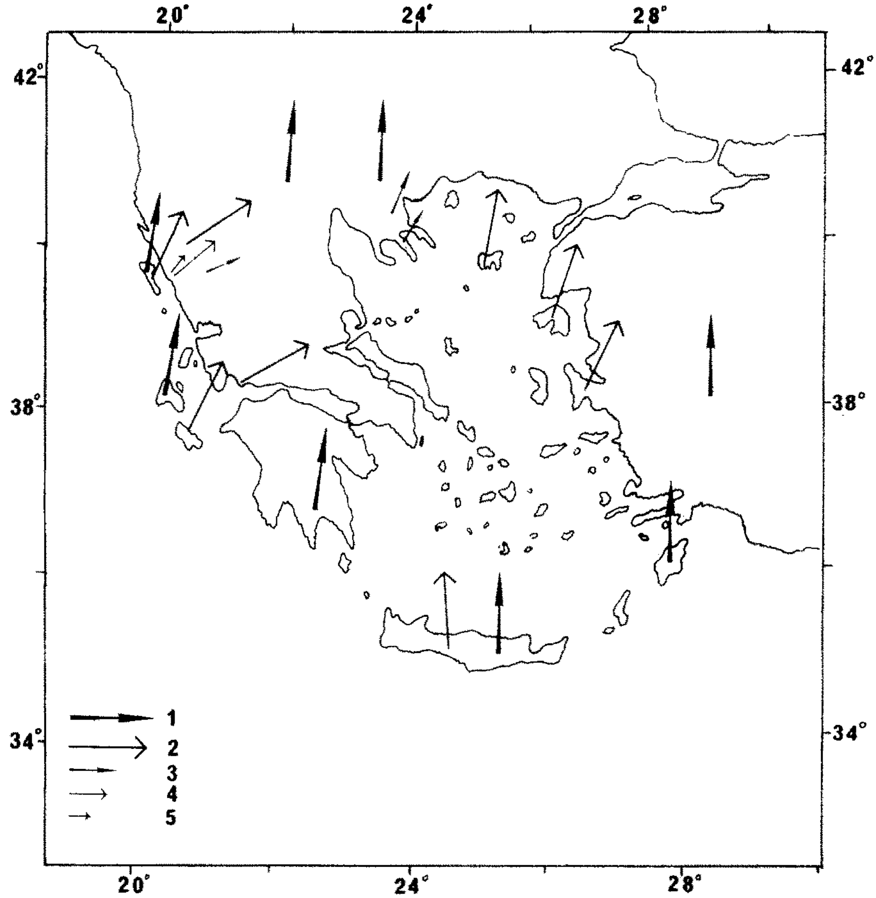

Fig. 7. Palaeomagnetic directions (mean declination) of Cenozoic formations in the Aegean area (after sources explained in the text). *1* = Plio-Quaternary, *2* = Miocene, *3* = Oligocene, *4* = Eocene, *5* = Palaeocene. The declination angle of magnetization, shown by the arrows, indicates the clockwise rotation of the Aegean.

ACKNOWLEDGEMENTS

Professor Seiya Uyeda and two anonymous reviewers read the manuscript and made constructive comments. We thank all of them. A first form of this paper was presented at the 19th General Assembly of the European Seismological Commission, Moscow, October 1–6, 1984.

REFERENCES

Angelier, J., 1979. Néotectonique de l'Arc Egéen. Soc. Geol. du Nord, Lille, Vol 3, 418 pp.

Angelier, J., Dumont, J., Karamanderesi, H., Poisson, A., Simsek, S. and Uysal, S., 1981. Analyses of fault mechanisms and expansion of southwestern Anatolia since the late Miocene. Tectonophysics, 75: T1–T9.

Båth, M., 1973. Introduction to Seismology. Birkhauser, Basel, 394 pp.

Boccaletti, M., Manetti, P. and Peccerillo, A., 1974. The Balkanids as an instance of back-arc thrust belt: possible relation with the Hellenids. Geol. Soc. Am. Bull., 85: 1077–1084.

Bott, M.H.P., 1982. The Interior of the Earth, its Structure, Constitution and Evolution. Elsevier, Amsterdam, 403 pp.

Caputo, M., Panza, G.F. and Postpischl, D., 1970. Deep structure of the Mediterranean Basin. J. Geophys. Res., 75: 4919–4923.

Comninakis, P.E. and Papazachos, B.C., 1982. A catalogue of earthquakes in Greece and surrounding area for the period 1901–1980. Geophys. Lab. Univ. Thessaloniki Publ., 5: 1–146.

Drakopoulos, J. and Delibasis, N., 1982. The focal mechanisms of earthquakes in the major area of Greece for the period 1947–1981. Seismol. Lab. Univ. Athens Publ., 2: 1–72.

Hasegawa, A., Umino, N. and Takagi, A., 1978. Double-planed deep seismic zone and upper-mantle structure in the northeastern Japan arc. Geophys. J.R. Astron. Soc., 54: 281–296.

Hodgson, J. and Storey, R., 1953. Tables extending Byerly's fault-plane techniques to earthquakes of any focal depth. Bull. Seismol. Soc. Am., 43: 49–61.

Horner, F. and Freeman, R., 1983. Palaeomagnetic evidence from pelagic limestones for clockwise rotation of the Ionian zone, Western Greece. Tectonophysics, 98: 11–27.

Isacks, B. and Molnar, P., 1969. Mantle earthquake mechanisms and the sinking of the lithosphere. Nature, 223: 1121–1124.

Isacks, B. and Molnar, P., 1971. Distribution of stresses in the descending lithosphere from a global survey of focal-mechanism solution of mantle earthquakes. Rev. Geophys. Space Phys., 9: 103–174.

Karnik, V., 1972. A note on the morphology and activity of seismic zones in the Aegean region. Nature, 239: 72–73.

Kissel, C., Jamet, M. and Laj, C., 1984. Palaeomagnetic evidence of Miocene and Pliocene rotational deformations of the Aegean Area. J. Geol. Soc. London, Spec. Publ., 17: 669–679.

Kissel, C., Laj, C., Mercier, J.L., Poisson, A., Savascin, Y. and Simeakis, K., 1985. Tertiary rotational deformations in the Aegean domain (Abstr.). EUG III Strasbourg, Terra Cognita, 5: 139 pp.

Kocaefe, S.S. and Ataman, G., 1982. Actual tectonics of the western Anatolia. Yerbilimleri, 9: 149–162.

Kondopoulou, D.P., 1982. Paléomagnetisme et déformations Néogenes du Nord de la mer Egée. Thèse Doct. 3e cycle, Univ. L. Pasteur de Strasbourg, 123 pp.

Kondopoulou, D.P. and Westphal, M., 1985. Paleomagnetism of the Tertiary intrusives from Chalkidiki (Northern Greece). J. Geophys., in press.

Kondopoulou, D.P., Papadopoulos, G.A. and Pavlides, S.B., 1985. A study of the deep seismotectonics in the Hellenic arc. Boll. Geof. Teor. Appl., in press.

Laj, C., Jamet, M., Sorel, D. and Valente, J., 1982. First palaeomagnetic results from Mio-Pliocene series of the Hellenic sedimentary arc. Tectonophysics, 86: 45–67.

Lauer, J.P., 1981. L'évolution géodynamique de la Turquie et de Chypre déduite de l'étude paleomagnétique. Thèse Doct. Etat, Univ. Strasbourg I, 300 pp.

Le Pichon, X. and Angelier, J., 1979. The Hellenic arc and trench system: a key to the neotectonic evolution of the eastern Mediterranean area. Tectonophysics, 60: 1–42.

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

Lyberis, N., Angelier, J., Huchon, P., Le Pichon, X. and Renard, V., 1982b. La Mer de Crète: Extension et Subsidence. Int. Symp. on the Hellenic Arc and Trench (H.E.A.T.). Proc., Athens, 1981, 1: 364–382.

Makris, J., 1976. A dynamic model of the Hellenic arc deduced from geophysical data. Tectonophysics, 36: 339–346.

Makropoulos, K.C. and Burton, P.W., 1984. Greek tectonics and seismicity. Tectonophysics, 106: 275–304.

McKenzie, D.P., 1969. Speculations on the consequences and causes of plate motions. Geophys. J.R. Astron. Soc., 18: 1–32.

McKenzie, D.P., 1972. Active tectonics of the Mediterranean region. Geophys. J.R. Astron. Soc., 30: 109–185.

McKenzie, D.P., 1978. Active tectonics of the Alpine-Himalayan belt: the Aegean Sea and surrounding regions. Geophys. J.R. Astron. Soc., 55: 217–254.

Mercier, J.L., 1981. Extensional-compressional tectonics associated with the Aegean Arc: comparison with the Andean Cordillera of south Peru–north Bolivia. Philos. Trans. R. Soc. London, Ser. A, 300: 337–355.

Mercier, J.L., Delibasis, N., Gauthier, A., Jarrige, J., Lemeille, F., Philip, H., Sebrier, M. and Sorel, D., 1979. La néotectonique de l'Arc Egéen. Rev. Géogr. Phys. Géol. Dyn., 21: 67–92.

Nakamura, K. and Uyeda, S., 1980. Stress gradient in arc–back arc regions and plate subduction. J. Geophys. Res., 85: 6419–6428.

Papadopoulos, G.A., 1982. Contribution to the study of the active deep tectonics of the Aegean and the surrounding areas. Sci. D. Thesis, Univ. of Thessaloniki, 176 pp. (in Greek with Engl. abstr.).

Papadopoulos, G.A., 1983. Seismotectonic properties of the Amorgos region (Cyclades, Greece). Bull. Geol. Soc. Greece, in press (in Greek with Engl. abstr.).

Papadopoulos, G.A., 1984. Cenozoic magmatism and deep tectonics in the Aegean area. Ann. Geol. Pays Hellen., in press.

Papadopoulos, G.A. and Andrinopoulos, A., 1984. Metallogenic evidence for palaeo-subduction zones in the Aegean area. Geol. Balcanica, 14.4: 3–7.

Papazachos, B.C., 1977. A lithospheric model to interpret focal properties of intermediate and shallow shocks in Central Greece. Pure Appl. Geophys., 115: 655–666.

Papazachos, B.C. and Comninakis, P.E., 1969. Aftershock sequences and crustal structure in the region of Greece. Natl. Obs. Athens, Seismol. Inst., Final Sci. Rep., June 1969.

Papazachos, B.C. and Comninakis, P.E., 1971. Geophysical and tectonic features of the Aegean arc. J. Geophys. Res., 76: 8517–8533.

Papazachos, B.C. and Comninakis, P.E., 1977. Modes of lithospheric interaction in the Aegean area. Int. Symp. on the Struct. Hist. Mediter. Basins, Split (Yugoslavia), October 1976. Editions Technip, Paris, pp. 319–331.

Papazachos, B.C. and Comninakis, P.E., 1982. A catalogue of historical earthquakes in Greece and the surrounding area, 479 B.C.–1900 A.D. Publ. Univ. of Thessaloniki, Geophys. Lab., 5: 1–24.

Papazachos, B.C. and Papadopoulos, G.A., 1977. Deep tectonic and associated ore deposits in the Aegean area. Proc. 6th. Colloq. Geology Aegean Region, 3: 1071–1080.

Papazachos, B.C., Kiratzi, A.A., Hatzidimitriou, P.M. and Rocca, A.C., 1984. Seismic faults in the Aegean area. Tectonophysics, 106: 71–85.

Paquin, C., Froidevaux, C., Bloyet, J., Rocard, Y. and Angelidis, C., 1982. Tectonic stresses on the mainland of Greece: in-situ measurements by overcoring. Tectonophysics, 86: 17–26.

Paquin, C., Bloyet, J. and Angelidis, C., 1984. Tectonic stresses on the boundary of the Aegean domain: "in situ" measurements by overcoring. Tectonophysics, 110: 145–150.

Pavlides, S.B., 1985. Neotectonic evolution of the Florina–Vegoritis–Ptolemais basin (W. Macedonia, N. Greece). Sci. D. Thesis, Univ. of Thessaloniki, 256 pp. (in Greek with Engl. abstr.).

Ritsema, A.R., 1958. Curves for bodily seismic waves of any focal depth. Meteorol. and Geophys. Inst. Djakarta, Verland, 54.

Ritsema, A.R., 1974. The earthquake mechanisms of the Balkan region. R. Neth. Meteorol. Inst., Sci. Rep., 74-4: 1–36.

Sleep, N. and Toksöz, M.N., 1973. Evolution of marginal basins. Nature, 233: 548–550.

Stegena, L. and Kolios, N., 1982. Stress determinations in the Aegean area using volcanic lineaments. Int. Symp. on the Hellenic Arc and Trench (H.E.A.T.). Proc., Athens, 1981, 2: 309–317.

Toksöz, M.N., Minear, J.W. and Julian, B.R., 1971. Temperature field and geophysical effects of a downgoing slab. J. Geophys. Res., 76: 1113–1138.

Uyeda, S., 1983. Comparative subductology. Episodes, 83-2: 19–24.