PARAMETERS OF TYPICAL FAULTS IN THE ACTIVE REGIONS OF THE AEGEAN AND SURROUNDING AREAS

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ABSTRACT

Eighty six reliable fault plane solutions of strong shallow earthquakes and instrumental as well as historical seismicity are used to accurately define the basic parameters of seismic faulting and the rate of crustal deformation in several regions of the Aegean and surrounding area.

Along the coastal area in northwestern Greece and west Albania, compressional crustal seismic (brittle) deformation at a rate of 4 mm/yr and in a N48°E causes thrust faults with a strike slip component. These faults strike parallel to the coast (strike=334°, dip =31°, rake=109°). In the convex side of the Hellenic arc (Zante-south of Crete-Rhodos) compressional seismic deformation at a rate of about 1cm/yr in a N34°E direction causes low angle thrust faults with an almost constant strike direction all along the arc (strike=300°, dip=25°, rake=96°). These two thrust zones are separated by the Cephalonia transform dextral fault (strike=45°, dip=61°, rake=173°) where slip takes place at a rate of 3 cm/yr, which the highest slip rate observed in the whole Aegean area. Along the whole external thrust area vertical crustal shortening takes place at a mean rate of 1 mm/yr.

In a tensional zone along the Hellenides mountain range (Pindos-Peloponnesus-Crete), horizontal extension, at a rate of 2 mm/yr and in a N108° E direction, generates normal faults with a small strike slip component. These faults strike almost parallel to the mountain range (strike=7° , dip=34° , rake=-98°). In a curved long zone, which includes south Bulgaria, north and central mainland of Greece, the south Aegean volcanic arc and southwest Turkey, extension at a rate of 5 mm/yr and in a N14°W direction generates normal faults with a small strike slip dextral component. These faults strike in an ENE direction (strike=72°, dip=47°, rake=-98°). In central western Turkey, an extension of the same value (5 mm/yr) acts in a N8°E direction and generates normal faults with a small strike slip dextral component. These faults strike in an almost east-weest direction (strike=93°, dip=47°, rake=-96°). Along the western part of the northern Anatolia fault zone, dextral strike slip motion with a normal component (strike=79°, dip=64°, rake=147°) takes place at a rate of 2 cm/yr, while in the north Aegean fault zone the motion takes place in strike-slip dextral faults (strike=48°, dip=86°, rake=-174°) at a rate of 1 cm/yr. Vertical thinning of about 1 mm/yr takes place in the Aegean Sea and surrounding countries.

The direction of maximum extension in the Aegean area shows an anticlockwise rotation of about 100° from east to west especially in the northern part of the area. It has a N26°E direction in the northwestern Anatolia, an almost north-south direction in northern Aegean, a N14°W in central Greece and a N72°W in the Hellenides mountain range of western Greece.

INTRODUCTION

The Aegean sea and surrounding area (figure 1) lies on the most active part of the Africa-Eurasia collision zone. The eastern Mediterranean lithosphere, which is the front part of the African lithosphere, is subducted beneath the Aegean along the Hellenic arc, which results in high shallow seismicity (magnitudes up to M_S=8.2) with thrust faults along the Hellenic arc and intermediate depth seismicity which forms a well defined Benioff zone in southern Aegean (Papazachos and Comninakis, 1971; Papazachos, 1990). However, the seismicity is not confined in the collision zone but expands in the back-arc Aegean area (Aegean sea, mainland of Greece, Albania, southern Yugoslavia, southern Bulgaria, Asia Minor), where it is expressed mainly with normal faults. Dextral strike-slip motion is observed in the North Anatolian fault and its continuation in the northern Aegean, especially along the North Aegean trough. This tectonic setting is attributed to the combination of an extension pattern due to the "roll-back" forces of the subduction and the westrward movement of Turkey.

This complicated tectonic image motivates for a detailed study of the seismic faults and velocity rates of the active crustal deformation. A lot of work has been done already, but the results are sometimes very controversial. For instance, along the convex side of the Hellenic arc values from 3 to 30 mm/yr have been calculated (Jackson and McKenzie, 1988 a, b; Papazachos et al., 1992). For the inner part, extensional velocities of the order of 3 to 30 mm/yr have been calculated (Tselentis and Makropoulos, 1986; Jackson and McKenzie, 1988b; Ekstrom and England, 1989; Ambraseys and Jackson, 1990; Papazachos, et al., 1991a, 1991b; Papazachos and Kiratzi, 1992; Papazachos et al., 1992) with an extreme of 60 mm/yr (Jackson and McKenzie, 1988a).

In the present paper, we present the parameters (strike, dip, rake) of the typical faults and the corresponding rate of crustal deformation in the active regions of the Aegean and surrounding area (34°N-43°N, 18°E-30°E).

METHOD OF ANALYSIS AND DATA

The method of analysis proposed by Papazachos and Kiratzi (1992) is used, which is based on the formulation of Kostrov (1974) and its expansion by Jackson and McKenzie (1988a). Briefly, the strain rate, $\dot{\varepsilon}$, and the velocity tensor, **U** , are calculated by the following equations:

$$\dot{\varepsilon}_{ij} = \frac{1}{2\mu V} \dot{M}_o \overline{F}_{ij} \quad i,j = 1,2,3 \tag{1}$$

$$U_{ii} = \frac{1}{2\mu l_k l_j} \dot{M}_o \overline{F}_{ii} \quad i \neq k, k \neq j, j \neq i, \; i = 1,2,3 \tag{2}$$

$$U_{12} = \frac{1}{\mu l_1 l_2} \dot{M}_o \overline{F}_{12} \tag{3}$$

$$U_{i3} = \frac{1}{\mu l_i l_3} \dot{M}_o \overline{F}_{i3} \quad i = 1,2 \tag{4}$$

where μ is the bulk modulus ($=3*10^{11}$ dyn/cm^2), V is the seismogenic volume (a parallele-piped prism with length, l_1, width, l_2, and depth extent, l_3), $\dot{M}_o$ is the seismic moment rate as it is determined from Molnar (1979), and F is the tensor calculated by:

$$\overline{F} = \frac{\dot{M}}{\dot{M}_0} = \frac{\sum_{n=1}^{N} M^n / t}{\sum_{n=1}^{N} M_0^n / t} = \frac{\sum_{n=1}^{N} M_0^n . F^n}{\sum_{n=1}^{N} M_0^n} \qquad (5)$$

The reference system in equations (1) to (5) is the zone's $0l_1l_2l_3$ system, so a rotation of $\overline{\mathbf{F}}$, usually calculated in the North-East-Down system, is necessary. In the present paper, $\overline{\mathbf{F}}$ was calculated as a simple average of the $\mathbf{F}^n$ tensors.

Two separate data sets are used: a) A set of fault plane solutions deduced either from recent instrumental data or from past reliable field observations to determine the stress field, which defines the "shape" of the deformation and b) all the available complete instrumental and historical data to calculate the moment rate released in each area which is consequently used for the determination of the "size" of the strain. The zonation of Papazachos and Papaioannou (1993) which separates the studied area in 68 seismic sources was adopted, shown in figure 2

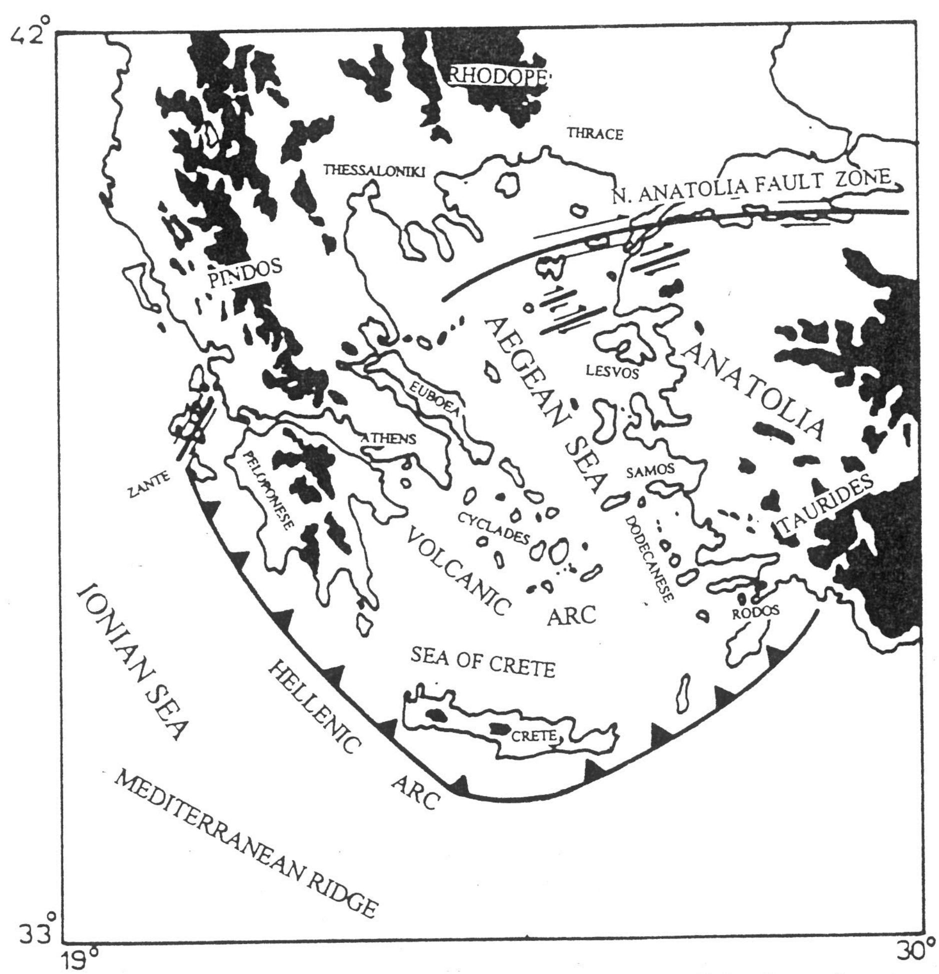

Fig.1. Schematic representation of the main tectonic features of the broader Aegean area.

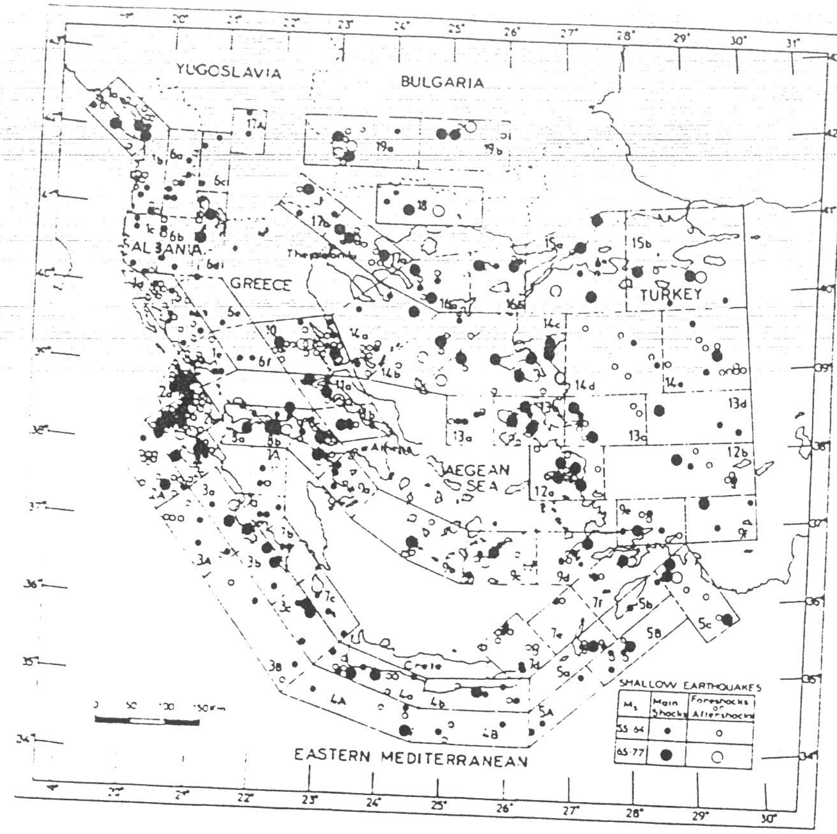

Fig.2. Map of the 67 sources and the relative seismicity determined for the Aegean area (Papazachos and Papaioannou, 1993).

together with the epicenters of the earthquakes with $Ms>5.5$. Papazachos and Panagiotopoulos (1994) separated Thessalia in two seismogenic regions (10a, 10b) so that the total number of these regions is 68. The rates of deformation are calculated for 63 sources, since no focal mechanisms were available for 5 seismic sources. All the information on the parameters used for each source are presented in Papazachos and Kiratzi (1994).

The fault plane solutions of the shallow events (h<40Km) with surface wave magnitude $M_S \geq 5.5$ which have occured in the studied area during the period 1963-1986 are shown in figure 3. The distribution of the focal mechanisms shows a spatial consistency of the direction of the stress field. Thus, the area was separated into 12 belts of similar focal mechanisms, within which the focal mechanism tensor, $\overline{\mathbf{F}}$, was estimated, as well as the corresponding to this tensor fault plane solution were determined. The same $\overline{\mathbf{F}}$ tensor was used for all the sources belonging to the same belt. However, the deformation for each of these sources varies, due to the different moment rates and to the different dimensions of each source.

TYPICAL FAULT PLANE SOLUTIONS AND CRUSTAL DEFORMATION

The fault plane solution corresponding to the tensor $\overline{\mathbf{F}}$ for each of the twelve belts can be considered as typical one for the belt and for each of the seismogenic regions (sources) which belong to this belt. Table 1 gives information on these typical fault plane solutions. The first three columns give the code number of the corresponding belt, the name of the belt and the code numbers of the seismogenic regions (sources) as these regions are shown in figure (2). In the next columns of this table, the parameters of the two nodal planes (strike, dip, rake) and of the T and P axes (azimuth, plunge) are given. From the two nodal planes the first one is considered as the most probable nodal plane.

Figure (4) shows the direction of the P axis (maximum compression) and of the T axis (maximum tension) in each source of the Aegean area.

It must be noted that information given on Table 1 is also of predictive significance because it gives the expected fault parameters in each region. This information is also of practical importance because these faulting parameters can be used to define the radiation pattern of the seismic waves for the major shocks in each region.

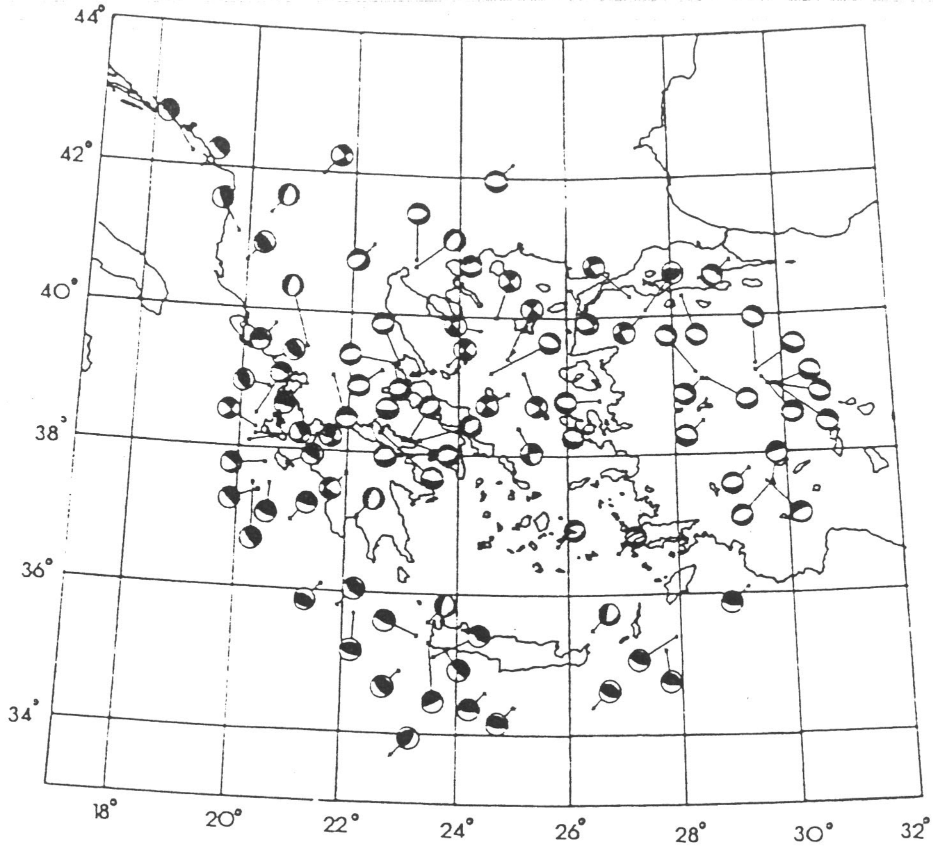

Fig.3. Equal area lower hemisphere projection for the 86 focal mechanisms used in the present study. The parameters of each fault plane solution are all listed and referenced in Papazachos and Kiratzi 1992.

Table 2 shows the eigenvectors and the eigenvalues of the crustal deformation velocity tensor for each seismogenic region of the area. The values (U_1, U_2,U_3) of these vectors are given (in cm/yr) as well as the azimuth, ξ (from north clockwise), and the plunge angle, δ (from the horizontal plane). Positive and negative values of U indicate tension and compression, respectively.

Figure (5) shows the maximum horizontal velocity (in mm/yr) for each region. Maximum compressional velocity is represented by convergent black arrow and maximum tensional velocity by divergent white arrows. In the cases of strike-slip faults only tensional velocities are given.

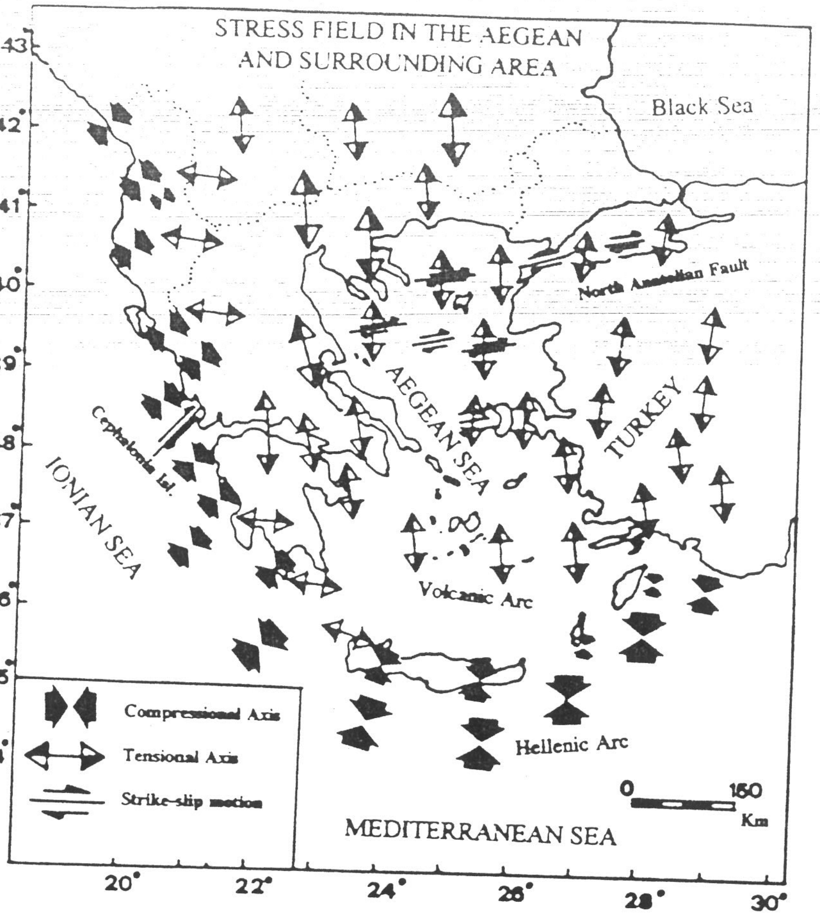

Fig.4 Direction of the typical compressional and tensional axes in the Aegean area.

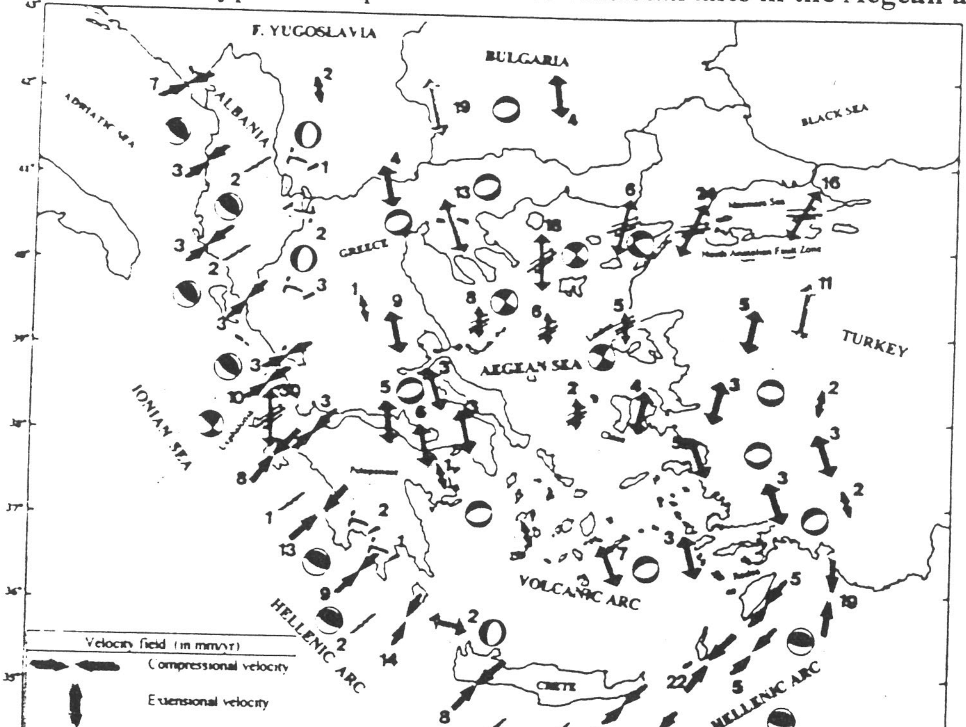

Fig.5 Distribution of the deformation velocities (in mm/yr) for the 63 sources for which data were used in the present study. The beach-balls represent the typical fault plane solutions for each source (black quadrants and white quadrants denote compression and extension, respectively).

RESULTS

Along the coastal belt in the northwest part of the investigated area (coast of Albania-northwestern coastal area of Greece), thrust faults with a dextral strike slip component trend parallel to the coast (strike=334°, dip=31°, rake=109°). In this belt, the maximum compressional deformation takes place at an average rate of 4 mm/yr in a N48°E direction.

In the convex side of the Hellenic arc, low angle thrust faults keep an almost constant northwest - southeast trend (strike=300°, dip=25°, rake=96°) all along the arc and dip to the concave part of the arc in its western part. The maximum compressional velocity is 8 mm/yr and has a N34°E direction.

The above described two thrust zones are separated by the Cephalonia strike slip dextral fault (strike=45°, dip=61°, rake=173°) where slip takes place at a rate of 3 cm/yr. This slip rate, which has been also determined by an independent method (B. Papazachos et al., 1994), is the highest one observed in the whole Aegean and surrounding area.

In the inner part of the area (Aegean sea and surroundings) crustal extension dominates. The direction of this stress field is not the same all over this area. An anticlockwise rotation of the maximum extensional deformation of about 100° from east (northwestern Turkey) to the west (Hellenides mountains) is observed and this extensional field can be separated into four domains:

1. Along the western boundary of the Aegean extensional field, a transitional zone of normal faulting with a small dextral component (belt 6 in table 1) has been identified (Papazachos et al., 1984). The typical faults in this zone strike parallel to the Hellenides mountain range (strike=7°, dip=34°, rake=-98°). The maximum horizontal deformation in this zone takes place at a rate of 2 mm/yr in a N108°E direction.
2. The second extensional domain is a curved zone of normal faulting with very weak dextral motion (strike=72°, dip=47°, rake=-98°) which includes southern Bulgaria, northern and central mainland of Greece, southern Aegean volcanic arc, southwestern Turkey (belts 7,8,9 in table 1). The extensional rate of deformation in this zone is 5 mm/yr in a N14°W direction.
3. A third extensional zone covers the central western Turkey (belt 10 in table 1) where normal faults with a very small dextral component strike in an about east-west direction (strike=93°, dip=47°, rake=-96°). Maximum tension takes place at a rate of 5 mm/yr in a N8°E direction.
4. The last domain in the Aegean area is the zone of dextral strike slip, with a considerable normal component, which includes the western part of the northern Anatolia fault (strike=79°, dip=64°, rake=-147°) and the northern Aegean strike slip faults (strike=48°, dip=86°, rake = -174°). It must be noted, however, that in northwestern Anatolia as well as in northern Aegean there are earthquakes which are produced by almost pure strike-slip dextral faults and other earthquakes which are produced by almost pure normal faults. The rate of motion is 2 cm/yr in the western part of the northern Anatolia fault and 1 cm/yr in the northern Aegean.

Table 1

Typical fault plane solutions for the 12 belts of similar stress field.

No	Belt Name	Sources	Fault pl.1 str/dip/rak	Fault pl.2 str/dip/rak	Taxis Az/Pl	Paxis Az/Pl
1	W.Albania-NW coasts of Greece	1a,1b,1c,1d,1e,2a,6a,6b	334/31/109	132/61/80	17/72	230/16
2	Cephalonia	2b	45/61/173	138/84/30	12/36	265/22
3	W.Hellenic Arc	2c,3a,3b,3c,3A,3B,8a	306/25/91	125/65/90	35/70	216/20
4	South Hellenic Arc	4a,4b,4A,4B	301/19/99	111/71/87	17/63	204/26
5	E.Hellenic Arc	5a,5b,5c,5A,5B	294/30/98	105/60/85	4/74	199/15
6	Hellenides mountain range	6c,6d,6e,7a,7b,7c	7/34/-98	197/57/-84	283/11	125/78
7	N. Greece	17a,17b,17A,19a,19b	68/46/-109	274/47/-72	351/1	258/77
8	Central Greece	8b,8c,10a,10b,11a,11b	258/41/-90	79/49/-90	168/43	50/86
9	Volcanic Arc	9a,9b,9c,9d,9e,9f,12a,12b	250/54/-94	77/37/-84	343/91	41/81
10	Central West. Turkey	13b,13c,13d,14d,14e	93/47/-96	281/44/-84	187/12	96/8
11	NW. Anatolia	15a,15b	259/64/-147	153/61/-30	25/2	117/41
12	N. Aegean	13a,14a,14b,14c,16a,16b	48/86/-174	318/84/-4	176/2	267/20

Table 2

Components of the velocity eigensystem ($U_{1,2,3}$) (in cm/yr). ξ and δ are the angles of azimuth and plunge of the eigenvector, respectively. Positive and negative values of U indicate tension and compression, respectively.

Source	U_1	ξ_1/δ_1	U_2	ξ_2/δ_2	U_3	ξ_3/δ_3
1a	.01	144/25	-.65	237/ 7	.11	341/64
1b	-.26	224/ 9	.00	132/15	.05	344/73
1c	.01	133/16	-.30	225/ 9	.06	344/72
1d	.01	138/28	-.30	231/ 7	.05	334/61
1e	.00	142/22	-.26	235/ 7	.05	342/67
2a	-.95	225/ 9	.01	132/13	.19	347/74
6a	-.22	223/ 7	.00	131/13	.03	341/75
6b	.00	134/17	-.15	226/ 9	.03	343/71
2b	2.08	2/ 8	-3.06	271/ 4	.02	154/82
2c	-.78	217/11	-.06	126/ 1	.17	33/79
3a	-1.34	212/ 9	-.13	302/ 2	.21	46/81
3b	-.88	215/11	-.07	305/ 1	.18	37/79
3c	-1.43	202/11	-.17	293/ 7	.30	56/77
3A	-.13	219/11	-.02	129/ 2	.03	28/79
3B	-.17	203/ 9	-.03	294/ 6	.03	56/79
8a	-.25	216/11	-.02	126/ 1	.05	33/79

4B	-.04	132/14	-.13	226/14	.03	359/70
5a	-2.16	213/ 4	-.07	122/13	.20	321/76
5b	-.51	211/ 7	-.02	120/12	.09	330/76
5c	-1.86	190/ 6	-.05	100/ 1	.25	2/84
5A	-.28	211/ 5	-.01	120/13	.03	322/76
5B	-.45	214/ 5	-.02	123/13	.05	323/76
6c	.00	15/ 8	.13	284/ 6	-.03	156/80
6d	.00	17/ 8	.24	286/ 8	-.07	150/79
6e	.00	19/ 5	.28	288/ 4	-.03	157/83
7a	.00	14/ 8	.24	282/ 7	-.06	151/79
7b	.00	19/ 5	.13	289/ 6	-.02	150/82
7c	.01	27/ 1	.15	297/ 6	-.03	126/83
8b	.52	168/ 2	.02	258/ 0	-.09	354/88
8c	.63	168/ 2	.03	258/ 0	-.11	355/88
10a	.89	173/ 2	.15	263/ 0	-.26	346/87
10b	.08	172/ 2	.01	262/ 0	-.01	345/88
11a	.33	162/ 2	.03	252/ 1	-.07	4/88
11b	.32	166/ 2	.03	256/ 0	-.07	358/88
9a	.10	343/ 4	.00	252/ 5	-.02	109/83
9b	.06	343/ 3	.00	252/ 5	-.01	98/84
9c	.71	343/ 5	.02	253/ 6	-.16	114/83
9d	.28	343/ 4	.01	252/ 5	-.04	106/83
9e	.29	341/ 4	.01	251/ 5	-.05	111/83
9f	.16	346/ 4	.00	255/ 6	-.03	108/82
12a	.50	342/ 3	.01	252/ 5	-.06	104/84
12b	.34	334/ 3	.02	244/ 1	-.04	127/87
13b	.38	189/ 0	.00	99/ 8	-.04	282/81
13c	.30	192/ 1	.00	102/ 8	-.04	285/82
13d	.15	187/ 0	.00	97/ 9	-.02	280/81
14d	.46	186/ 0	-.01	96/ 9	-.05	280/81
14e	1.14	186/ 1	-.02	95/ 9	-.12	279/81
17a	1.30	158/ 1	.08	67/18	-.31	250/72
17b	.40	351/ 0	.00	81/22	-.08	260/68
17A	.19	350/ 0	.00	80/19	-.06	259/71
19a	1.91	350/ 0	.00	80/24	-.35	259/66
19b	.36	355/ 1	.00	86/24	-.08	264/66
15a	2.38	26/ 0	-1.33	116/ 5	-.07	292/85
15b	1.57	26/ 0	-.88	116/ 4	-.04	291/86
13a	.19	183/ 0	-.20	273/ 2	-.01	81/88
14a	.84	184/ 0	-.53	274/ 1	-.02	85/89
14b	.58	182/ 0	-.69	272/ 1	-.02	77/89
14c	.52	182/ 0	-.74	272/ 1	-.01	72/89
16a	1.80	183/ 0	-2.40	273/ 1	-.07	76/89
16b	.64	183/ 0	-.46	273/ 1	-.02	83/89

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