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RATES OF ACTIVE CRUSTALDEFORMATION IN THE AEGEAN AND THE SURROUNDING AREA

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ABSTRACT

Active crustal deformation is estimated for 26 shallow seismic zones of the Aegean and the surrounding area. The "size" of the deformation is estimated by the use of all available complete samples of instrumental and historical data (magnitudes, epicentres) for each seismic zone, and the "shape" of the deformation is determined by all reliable fault plane solutions for each of 11 broader seismic belts.

Crustal shortening occurs all along the western and southern coast of the area (Adriatic, Ionian, eastern Mediterranean). Along the western coast of Yugoslavia, Albania and central Greece the shortening rate is around 2mm/yr in a direction perpendicular to the coast line (N47°E). In the Ionian islands (Leukada, Cephalonia, Zante) shortening of 10 mm/yr in an almost east-west direction (N83°E) together with extension of 11 mm/yr in an almost north-south direction (N174°E) occurs. The upper crust along the convex side of the Hellenic arc (south of Peloponesus, Crete, Rhodos) is compressed at a rate of 6 mm/yr in a direction of N34°E.

In the Aegean Sea and the surrounding lands (mainland of western and northern Greece, southern Yugoslavia and Bulgaria, western Turkey) the seismic deformation is taken up by an almost NS extension at a mean rate of 5 mm/yr.

In the Northern Anatolia and Northern Aegean fault zones the deformation is controlled by the westward movement of the North Anatolian fault. Northern Anatolia is undergoing a N115°E compression at a rate of 22 mm/yr which is relieved by a N25°E extension at a rate of 19 mm/yr, and the Northern Aegean is undergoing EW compression at a rate of 16 mm/yr as well as NS extension at rate of 8 mm/yr.

A vertical crustal thickening of the order of 0.3 mm/yr is observed in the compressional zone along the western and southern coastal zone, while a vertical crustal thinning of about 0.8 mm/yr is observed in the inner broad extensional Aegean area.

In the western part of the area and between the external compressional field and the internal extensional field, a belt with an almost north-south orientation exists (eastern Albania-western

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mainland of Greece up to the western corner of Crete). This zone is dominated by an extension of 1.6 mm/yr in the direction N112°E. A vertical thinning of 0.2 mm/yr is also observed in this belt.

INTRODUCTION

The Aegean and the surrounding area is considered to be one of the most seismically active regions of the world. Destructive shallow earthquakes with M_S values up to 7.8, and intermediate depth earthquakes, with even larger magnitudes, up to 8.2, have repeatedly struck many sites of this area. Therefore, a good knowledge of the geodynamics of the region is of primary importance from both the theoretical and the practical point of view.

The most prominent features of tectonic origin in this area are, from south to north, the **Mediterranean Ridge**, a compressional submarine accretionary prism of material which extends from the Ionian Sea to Cyprus and follows the trend of the Hellenic arc, the **Hellenic Trench** with a maximum water depth of 5Km, the **Hellenic Arc**, which consists of the outer sedimentary arc and of the inner volcanic arc, and finally the **back-arc Aegean** area, which includes the Aegean Sea, the mainland of Greece, Albania, south Yugoslavia, south Bulgaria and western Turkey. In this paper an attempt is made to quantify the deformation rates in this area as they are deduced from seismic moment rates and focal mechanism data. It is of primary importance to have the rate that strain (or deformation) is accummulated for any seismic hazard analysis and further studies.

Previous work for estimating crustal deformation in several parts of this area has been made by several investigators. Most of this work concerns the inner part of the Hellenic arc which includes the southern and central Aegean, central eastern Greece and central western Turkey. In this region, which is dominated by an extensional tectonic field of north-south direction, values of velocity rates in this direction have been calculated. These values usually vary between 5 and 22 mm/yr (Eyidogan, 1988; Ekstrom and England, 1989; Papazachos et al., 1990; Ambraseys and Jackson, 1990) but values down to 3 mm/yr (Tselentis and Makropoulos, 1986) and up to 60 mm/yr (Jackson and McKenzie, 1988a,b) have been also reported. Eyidogan (1988) indicates the dominant mode of deformation in Marmara province (northwest Anatolia fault system) to be right lateral shear of the order of 24 mm/yr, while Kiratzi (1991) estimated a velocity rate of 15 mm/yr of EW compression relieved by 9 mm/yr of north-south extention in the northern Aegean area where right lateral strike-slip faulting also prevails. Anderson and Jackson (1987) calculated a seismic shortening of 2 mm/yr in the Adriatic region along a direction normal to the coast. Such shortening also occurs along the convex side of the Hellenic arc where Jackson and McKenzie (1988a) estimated a subduction rate of 100 mm/yr, later reduced to 15 mm/yr (Jackson and McKenzie, 1988b), while Tselentis et al. (1988) calculated a subduction rate of 11 mm/yr along the western part of this arc.

The method of analysis applied in the papers mentioned above, for the estimation of active crustal deformation, requires the knowledge of both the fault plane solution (strike, dip, rake) and the seismic moment for each earthquake of the data sample. Keeping in mind that reliable fault plane solutions exist only for mainly recent large earthquakes (since when the worldwide long period standardized stations are in operation) this method of analysis limits its application to a observational period of only 30 years and to only strong earthquakes. It is possible to extend this period, by assuming the fault parameters of the past earthquakes, and this has been done by some researchers. However, since this method of analysis requires complete data (all earthquakes larger than a certain magnitude threshold) and for only few of these earthquakes these parameters can be reliably estimated (for those for which surface fault trace was clearly observed), this extension back in time may introduce considerable errors and biases because these events are large (they have a large seismic moment) and their assumed focal mechanism strongly controls the resulting deformation tensor. We believe that this is the main reason for which rather controversial results have been published so far for the Aegean area.

Two of the present authors (Papazachos and Kiratzi, 1992), in an attempt to overcome the mentioned drawbacks, suggested a method of analysis, which permits: a) the use of all available complete data, which include information on smaller recent shocks and on strong instrumental and historical earthquakes of a much longer period for the seismic moment rate calculation in a seismic zone, and b) fault parameters deduced from reliable fault plane solutions of recent strong earthquakes and from reliable field observations of past strong earthquakes which occurred in a broader seismic belt.

The purpose of the present paper is to present the main results of the application of this method in 26 shallow seismic zones of the Aegean and surrounding area. More detailed information on this work will be presented elsewhere.

METHOD OF ANALYSIS AND DATA

The method applied in the present paper for estimation of active crustal deformation in the Aegean and surrounding area is that proposed by Papazachos and Kiratzi (1992). These researchers calculated the velocity of deformation in two steps. Initially the "size" of the deformation, represented by the annual scalar moment rate, $\dot{M}_o$, is calculated in each zone using the relations defined by Molnar (1979). Then the "shape" of the deformation is defined for each seismic belt (including one or more zones of the same seismotectonic features) as is described in the following.

We calculate the tensor:

$$F^n = \frac{M^n}{M_o^n} \qquad (1)$$

for each fault plane solution using the relations of Aki and Richards (1980), where M^n is the moment tensor and M_o^n the corresponding scalar moment. A "representative focal mechanism tensor", $\bar{F}$, is calculated for each belt using the following relations:

$$\bar{F} = \frac{\sum_{n=1}^{N} M_o^n F^n}{\sum_{n=1}^{N} M_o^n} \qquad (2)$$

where N is the number of focal mechanisms which are available in each belt. The equations initially defined by Kostrov (1974) and Jackson and McKenzie (1988) can now be transformed and the velocity tensor is calculated using the following relations:

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

$$U_{12} = \frac{1}{\mu l_1 l_2} \dot{M}_o \bar{F}_{12} \qquad (3)$$

$$U_{i3} = \frac{1}{\mu l_1 l_3} \dot{M}_o \bar{F}_{i3} \qquad i=1,2$$

where μ is the bulk modulus and l_1, l_2 and l_3 denote the length, width and thickness of each zone respectively.

The method described above requires two sets of data. The first set includes the data (epicenters, magnitudes) which are needed for the estimation of the moment rate in each seismic zone, while the second set of data includes fault plane solutions (strike, dip, rake) and the corresponding magnitudes which are needed for the determination of the "shape" of deformation in each seismic belt.

As source of data for the magnitudes and epicenters of earthquakes, the catalogue of Comninakis and Papazachos (1986) was used for the period 1901-1985 and the monthly bulletins of the National Observatory of Athens and of the Geophysical Laboratory of the University of Thessaloniki for the period 1986-1990. For the historical earthquakes (before the present century) such information was taken from the book of Papazachos and Papazachou (1990).

The whole area has been separated into 26 seismic zones shown in figure (1). This separation of the area in seismic zones is similar to that made by Papazachos (1990) with some modifications made for the purpose of the present work which requires rather broad zones. A code number is given to each seismic zone (1a, 1b, 1c, 2...) and this number is also kept in table 1 where information on the completeness of the data, the maximum magnitude and the results of the present work are given. The data for each seismic zone have been separated in groups according to their completeness. The second and third column of table 1 show the time (year) since when the data are complete for each magnitude range and the minimum magnitude of this range, respectively. For the first zone, 1a, for example, the complete data groups are all shallow earthquakes with $M_S \geq$ 6.5, 5.5, 5.0 and 4.5 for the periods 1855-1990, 1901-1990, 1950-1990 and 1965-1990, respectively. Figure (1) also shows the epicenters of the earthquakes of the complete groups of data.

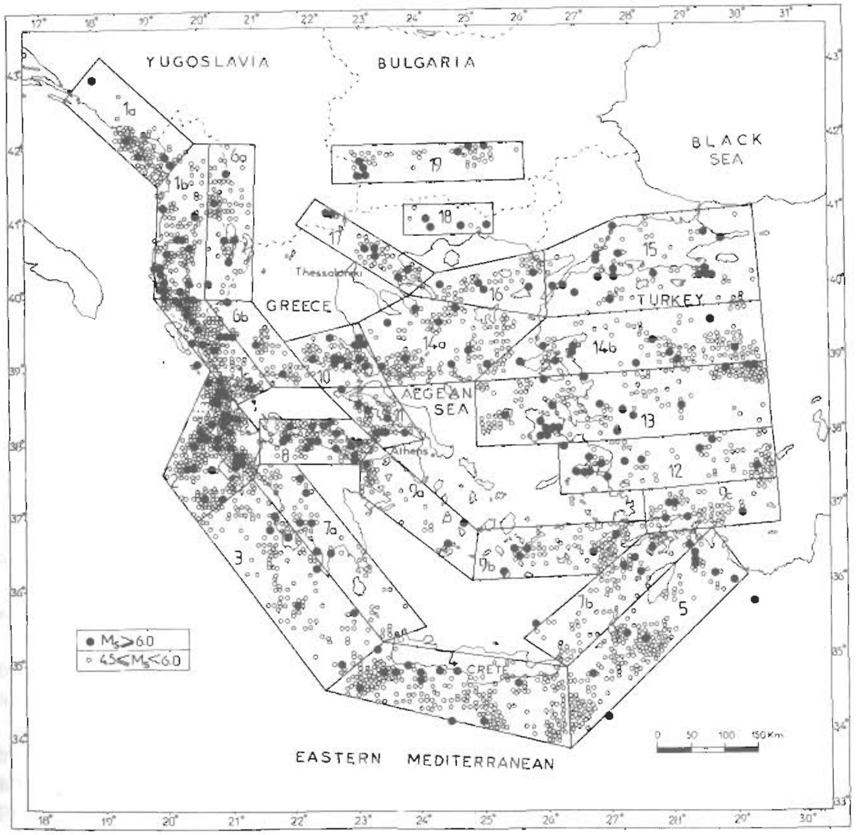

Figure 1. The 26 seismic zones in the Aegean and surrounding area where crustal deformation is determined.

The annual scalar moment release calculation requires the knowledge of the constants c and d of the linear relation between the logarithm of the seismic moment, M_o, and the magnitude, M_S, of the shock, as well as the constants a and b of the frequency-magnitude Gutenberg-Richter relation, and the maximum magnitude M_{max}, of each zone. The values c=1.5, d=18.89 (Papazachos and Kiratzi, 1991) were considered as the most reliable for the first two parameters, while the values of a and b were calculated for each seismic zone by a method known as "mean value" method (Milne and Davenport, 1969) which is decribed in detail by Papazachos (1990). The maximum magnitude for each zone is the magnitude of the largest earthquake ever observed in the zone.

As it is seen in figure (1), in some cases the area covered by epicenters does not necessarily cover the whole seismic zone. Since we are interested in the active part of each zone and because for the purpose of the present paper we need to have zones of rectangular shape, we assumed that the epicentral area of each zone has such shape. Thus, the length, the width and the azimuth of each zone were calculated as follows: Using the complete data set we calculated the coordinates of the center of the zone which we choose as the center of a coordinate system with x and y axes parallel to NS and EW direction, respectively. Assuming that the earthquakes in each zone generally follow a linear pattern, we calculated a least squares' best fit line for each zone. The projections of the most distant epicenters, from the center of the zone, onto this line define the length, l_1, of the zone. The width, l_2, of the zone is taken to be 4σ, where σ is the standard deviation of the earthquake epicenters from the line and, finally, the azimuth, ξ, is taken to be the azimuth of the line with the North. The value of l_3 (depth extent of the seismogenic layer) was taken to be 15 Km for all zones of shallow seismicity.

The source of information for the fault plane solutions is the catalogue published by Papazachos et al. (1991) and includes information (strike, dip, rake) for strong earthquakes which have occurred during the period 1956-1986. Such information has been also used for five past earthquakes for which reliable field observations are available (Papazachos and Papazachou, 1990).

The seismic zones have been grouped in the following seismic belts of similar fault plane solutions and the "shape" tensor, **F**, of each belt has been determined by means of the available fault plane solutions of the corresponding belt.

Belt 1. Coast of Yugoslavia, Albania and western Greece. It includes seismic zones 1a, 1b and 1c. The fault plane solutions of these earthquakes show thrust faulting with the fault planes parallel to the coast. They are produced by compressional forces due to the collision of two continental lithospheres, the Apulian and Eurasian, without any evidence of soubduction.

Belt 2. Ionian islands. It includes seismic zone 2. Fault plane solutions are of thrust type except for two of them in the central part of the zone which are of strike-slip type.

Belt 3. Convex side of the Hellenic arc. It includes seismic zones 3, 4 and 5. All fault plane solutions show thrust type faulting.

Belt 4. Eastern Albania and central western Greece. This belt strikes in an about north-south direction and includes seismic zones 6a, 6b and 7a. All fault plane solutions in this belt show normal faulting with an almost north-south strike which is produced by an east-west extension.

Belt 5. Central Greece. It includes zones 8, 10 and 11. The fault plane solutions of this belt show normal faulting in mainly EW striking planes.

Belt 6. Volcanic arc. It includes zones 9a, 9b and 7b and covers the area of the volcanic arc.

Belt 7. Samos and southwestern Turkey. It includes zones 9c and 12.

Belt 8. Chios, Lesbos and central western Turkey. It includes zones 13 and 14b.

Belt 9. Northern Anatolia. It includes seismic zone 15 which is extended along the westernmost end of the North Anatolian fault.

Belt 10. Northern Aegean. It includes zones 14a and 16. The fault plane solutions of this area mainly show strike-slip faulting.

Belt 11. Central Macedonia and southern Bulgaria. It includes seismic zones 17, 18 and 19.

VELOCITY RATES

Following the procedure suggested by Papazachos and Kiratzi (1992) and using the data described above, the eigenvectors of the velocity tensor were calculated in all 26 seismic zones of shallow shocks indentified in the Aegean and the surrounding area. Table 1 summarises the results for each seismic zone. The velocities , Vel (eigenvalues) are given in mm/yr. The azimuth, Az, and the dip, of the vectors are also given in this table (extension is positive and shortening is negative), except for the velocity in the vertical direction (thinning is negative and thickening is positive). The dip angle is possitive when the eigenvector axis lies <u>in</u> the solid earth and negative when it lies <u>above</u> the solid earth.

Figure (2) is a map which graphically illustrates the horizontal velocity rates in the seismic zones which are deformed. The length of the arrows is indicative of the magnitude of the velocity rate. The following observations can be made on the basis of information given on table 1 and figure (2):

The dominant mode of deformation along the coast of Yugoslavia, Albania and western central mainland of Greece is shortening at a mean rate of 2±0.5mm/yr in a mean direction of N47°±8°E which is approximately perpendicular to the coast line.

A shortening of 10 mm/yr in an almost east-west direction (N83° E) and an extension of 11 mm/yr in an almost north-south direction N174°E) occurs in the seismic belt of the Ionian islands.

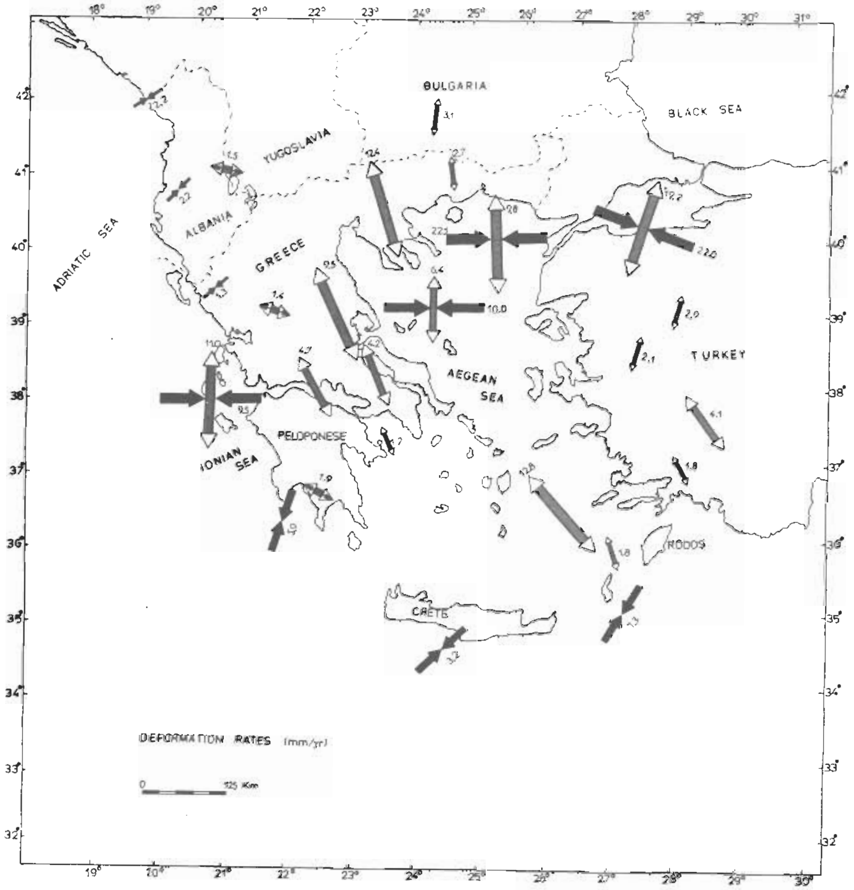

Figure 2. Schematic representation of the eigenvectors of the velocity tensor for the 26 seismic zones of the Aegean and the surrounding area. (The number next to the arrow shows the absolute value of the velocity in mm/yr).

Along the convex side of the Hellenic arc the shallow seismicity contributes to crustal shortening by 5.5±1.7 mm/yr which takes place in N34°±13°E direction. We believe that this value of shortening is too small to account for the subduction rate under the Aegean arc. This subduction rate must be determined by the moment rate and focal mechanisms of the intermediate depth earthquakes which occur in the zone of collision between the subducted eastern Mediterranean lithosphere and the Aegean lithosphere (Papazachos, 1990) and such work is in progress. Preliminary results show a contribution of these intermediate depth earthquakes to the subduction rate of the order of 2-3 cm/yr.

The whole Aegean area (Aegean sea, eastern mainland of Greece, southern Yugoslavia and Bulgaria, western Turkey) is dominated by an extensional field. If we exclude the results for the northwest Anatolia and north Aegean fault zones, where horizontal compression also occurrs, the mean rate of expansion in this broad area of normal faulting is about 5 mm/yr in an about north-south direction.

Deformation in the northwestern Anatolia is expressed as compression at a rate of 22 mm/yr in a N115°E direction and as extension at rate of 19 mm/yr in a direction N25°E. The average compression in the North Aegean fault zones is 16 mm/yr in a N88°E direction and the average extension is 8 mm/yr in a N178°E direction.

Table 1. Information on the data used and on the results (eigenvector of the velocity tensor) of the present work (see text for information on the notation).

Zone	t	M_{min}	M_{max}	Vel	Az°	Dip°
1a	1855	6.5	7.1	-2.3	58	-24
	1901	5.5		0.1	140	16
	1950	5.0		0.3		
	1965	4.5				
1b	1833	6.2	6.7	-2.2	39	-18
	1901	5.5		0.1	135	-21
	1917	5.0		0.2		
	1965	4.5				
1c	1809	6.1	6.5	-1.2	43	-26
	1901	5.5		0.0	136	-7
	1917	5.0		0.2		
	1965	4.5				
2	1767	7.2	7.2	-9.5	83	-9
	1825	6.3		11.0	174	-7
	1901	5.5		0.4		
	1911	5.0				
	1965	4.5				
3	1866	6.5	7.5	-5.9	17	-8
	1925	5.0		0.2	110	-24
	1965	4.5		0.5		
4	1805	6.7	7.2	-3.2	48	-10
	1901	5.5		-0.3	135	15
	1919	5.0		0.3		
	1965	4.5				
5	1851	7.2	7.2	-7.3	37	-5

	1911	5.5		-0.1	126	12
	1919	5.0		0.4		
	1965	4.5				
6a	1843	6.2	6.7	1.5	112	-7
	1901	5.5		-0.1	23	8
	1920	5.0		-0.0		
	1965	4.5				
6b	1901	5.5	6.5	1.4	108	-4
	1911	5.0		-0.2	14	-41
	1965	4.5		-0.2		
7a	1842	6.4	6.5	1.9	115	-3
	1901	5.5		-0.1	25	6
	1911	5.0		-0.1		
	1965	4.5				
7b	1842	6.4	6.8	1.8	165	-3
	1911	5.0		-0.1	75	-4
	1965	4.5		-0.3		
8	1748	6.6	7.0	4.7	152	2
	1858	6.0		-0.1	61	2
	1901	5.5		-0.9		
	1911	5.0				
	1965	4.5				
9a	1733	6.4	6.5	1.2	155	-2
	1911	5.0		-0.1	65	0
	1965	4.5		-0.1		
9b	1866	6.2	7.5	12.8	141	-2
	1901	5.5		-1.2	52	12
	1911	5.0		-1.9		
	1965	4.5				
9c	1869	6.8	6.8	1.8	148	-6
	1901	5.5		-0.1	58	4
	1920	5.0		-0.4		
	1965	4.5				
10	1901	5.5	7.0	9.5	154	2
	1911	5.0		-0.5	64	3
	1965	4.5		-2.1		
11	1758	6.8	7.0	4.2	158	1
	1874	6.0		-0.8	68	-9
	1901	5.5		-0.6		
	1965	4.5				
12	1873	6.0	7.0	4.1	141	-4
	1901	5.5		0.0	52	8
	1918	5.0		-0.5		
	1965	4.5				
13	1845	6.2	6.8	2.1	23	-6
	1901	5.5		0.0	112	13
	1920	5.0		-0.3		
	1965	4.5				
14a	1868	6.2	7.2	6.4	179	1
	1911	5.0		-10.0	89	-1
	1965	4.5		-0.1		
14b	1845	6.7	7.1	2.9	18	-8
	1901	5.5		-0.0	107	9
	1920	5.0		-0.5		
	1965	4.5				
15	1766	7.4	7.7	19.2	25	0
	1855	6.2		22.0	115	3
	1901	5.5		-0.5		
	1911	5.0				
	1965	4.5				
16	1859	6.5	7.5	9.8	177	1
	1911	5.5		-22.1	87	-1
	1930	5.0		-0.1		
	1965	4.5				
17	1901	5.5	7.0	12.4	162	0
	1911	5.0		-0.4	72	4
	1965	4.5		-2.4		
18	1784	6.0	7.3	2.7	170	0
	1901	5.5		-0.2	80	4
	1911	5.0		-1.0		
	1965	4.5				
19	1750	6.8	7.7	3.1	4	0
	1901	5.5		-0.3	94	5
	1965	4.5		-1.1		

In the seismic belt which has an about north-south trend and lies between the external compressional area and the inner extensional area, including eastern Albania and the west mainland of Greece up to the western corner of Crete, extention of 1.6±0.2 mm/yr in a direction N112°±3°E occurs.

The average vertical crustal thickening in the compressional zone along the western and southern coast of the area is 0.3±0.1 mm/yr, while the average crustal thinning in the Aegean area which is dominated by north-south extension is 0.8±0.7 mm/yr.

It may be empasized that the deformation rates calculated in the present paper express the seismic part of information and do not include the anelastic part. Billiris et al. (1991) determined the whole deformation in central Greece by geodetic measurements and found a north-south extension equal to about 11 mm/yr, that is, about two to three times the seismic extension calculated in the present paper. This is a plausive result and an independent evidence in favour of the methodology applied and the results obtained in the present paper.

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