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# GEOPHYSICS

# SEISMOTECTONIC STRAIN OF LITHOSPHERE IN THE AEGEAN REGION

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**Seismotectonic strain rate tensors, the main and effective strain rates for the lithosphere of the Aegean region have been computed. The orientation of the compressive and tensile strain axes has been determined. The relationship between possible failure of the medium and the effective strain rate has been established for the first time. Observation of strong 1991–1997 earthquakes has shown that regions of high seismic hazard are those where the strain rates are at their minimum.**

## PROBLEM STATEMENT AND RESEARCH METHODS

Seismotectonic strain of an actual geophysical medium is as a rule associated with irreversible processes in earthquake sources [1]. Because of the mechanism of internal friction between the sides of a rupture, a strike-slip fault typical of most earthquakes can be represented as a viscous failure that is related to low medium loading rates and is accompanied with plastic strains [2, 3].

In a principal strain space, the medium failure condition is formulated as the Mises–Henka criterion [3]. At low strains which we are dealing with in this particular case, this criterion can also be stated for strain rates whose tensor differs from the strain tensor only by a time factor. Under this condition the critical strain rate $\dot{\varepsilon}_0$ that characterizes the start of the continuum failure process will be [2]

$$\left[(\dot{\varepsilon}_1 - \dot{\varepsilon}_2)^2 + (\dot{\varepsilon}_2 - \dot{\varepsilon}_3)^2 + (\dot{\varepsilon}_3 - \dot{\varepsilon}_1)^2\right]^{1/2} \le \sqrt{2}\,\dot{\varepsilon}_0, \tag{1}$$

where $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$, $\dot{\varepsilon}_3$ are the principal values of the strain rate tensor. This formula combines the plastic flow condition and the strain criterion of failure.

The seismotectonic strain rate is computed by summing up matrices formed from the dyadic products of the normal and the fault vectors. It is assumed that orientation of residual displacements caused by earthquakes coincides with the direction of rupture. The seismotectonic strain rate tensor can be determined as follows [1, 3–5]:

$$\dot{\varepsilon}_{ik} = \frac{1}{2\mu VT}\sum_{j=1}^{N} M^0_{j,ik}, \tag{2}$$

where $\sum_{j=1}^{N} M^0_{j,ik}$ is the total seismic moment of earthquakes, $\mu$ is the modulus of natural elasticity of the medium, $V$ is the seismogenic volume, and $T$ is the observation period. The components of the seismic moment tensor $M^0_{j,ik}$ are computed from the angular parameters of earthquake source mechanisms [5]. The basic contribution to seismotectonic strain is made by strong earthquakes, so low-magnitude earthquakes can be neglected.

The seismotectonic strain rate tensor $\dot{\varepsilon}_{ik}$ thus derived is a deviator. Its quadratic invariant found in [2, 3]

$$I_2 = \frac{1}{6}\left[(\dot{\varepsilon}_1 - \dot{\varepsilon}_2)^2 + (\dot{\varepsilon}_2 - \dot{\varepsilon}_3)^2 + (\dot{\varepsilon}_3 - \dot{\varepsilon}_1)^2\right]^{1/2} \tag{3}$$

describes the effective strain rate and is equal to the left-hand side of (1) accurate to the multiplier.

The objective of this study was the computation of the seismotectonic strain rate tensor, its principal values and invariants. These quantities were also used to determine orientation of the compressive and tensile strain axes and to identify regions of high seismic hazard [6] for their subsequent comparison with the observations, namely, with the epicenters of predicted strong earthquakes.

## TECTONICS AND SEISMICITY OF STUDY REGION

The geological data testify to diversified block structure of the Aegean region typical of both the Earth's crust and the upper mantle down to a depth of at least 200 km. The following block structures are identifiable: the African plate margin; the region of the outer Ellinides and Taurus Mountains that forms the Hellenic arc structures; the South Aegean plate including the Cretian basin; the western Turkey graben zones; the Rhodes and Pontic blocks in northern Greece. The average thickness of the Earth's crust is about 50 km in western Greece, 30 km in the central area of the Aegean Sea, 40 km in western Turkey, and 10 km in the lithosphere of the Mediterranean Sea [7–10].

According to seismic tomography data, a thick asthenospheric zone is observed in the lithosphere of the Aegean region. This zone starts on the surface in the area of the Hellenic arc and dipping at an angle of 35° northward down to a depth of 400 km. In the northern part of the Aegean Sea and under the Sea of Marmara it is traceable down to a depth of 180 km. The boundaries of the asthenospheric zone coincide with the active Benioff zone [7, 11]. Areas of the maximum seismic activity within the crust are mostly associated with large fault structures extending to the surface. The volcanic arc area is characterized by weak seismic activity [12–14]. The lithosphere of the southern Aegean Sea is a quasi-homogeneous structure that expands and at the same time oscillates in an almost east-west direction due to which seismic activity is high at its edges. On the surface there is an alternation of compression and extension areas [14].

Strain processes in the region were studied by various authors [8–12, 14]. Interaction of the lithospheres of the Mediterranean and Aegean Seas is responsible for a compressive strain component directed along the African continent thrust to under Eurasia. Another powerful tectonic process is sliding along the North-Anatolian fault and its continuation in the northern part of the Aegean Sea which causes a southwestern displacement of some individual structures of the continental portion of the South Aegean block. The Mediterranean plate forms reverse faults in the outer part of the Hellenic arc. This causes a rise of the Earth's crust matter, its cracking and, as a result, thickening of the seismogenic layer with the formation of smaller block structures [7, 14]. In all the above works the study of strains was limited to determination of the orientation of strain processes.

## INITIAL DATA

The data used in this study were taken from the catalog of the source mechanisms of 1964–1990 earthquakes [15] and also from the Harvard catalog for a period of 1991–1998. The study region was the area within (20–30)° E and (34–42)° N. Figure 1 shows a map of epicenters of different-magnitude earthquakes. The range of magnitudes considered was $4.2 \le Mw \le 6.3$, where $Mw$ is an instantaneous magnitude. In the period under study, the strongest earthquake of the reverse thrust type occurred on March 31, 1995 at a depth of 45 km in the Gulf-of-Corinth area. The Gulf of Corinth was found to be an area of maximum seismic activity. Another earthquake (6.0 magnitude) occurred in the same area on June 15, 1995. As can be seen from Fig. 1, there were no really strong earthquakes in the southern part of the Aegean Sea.

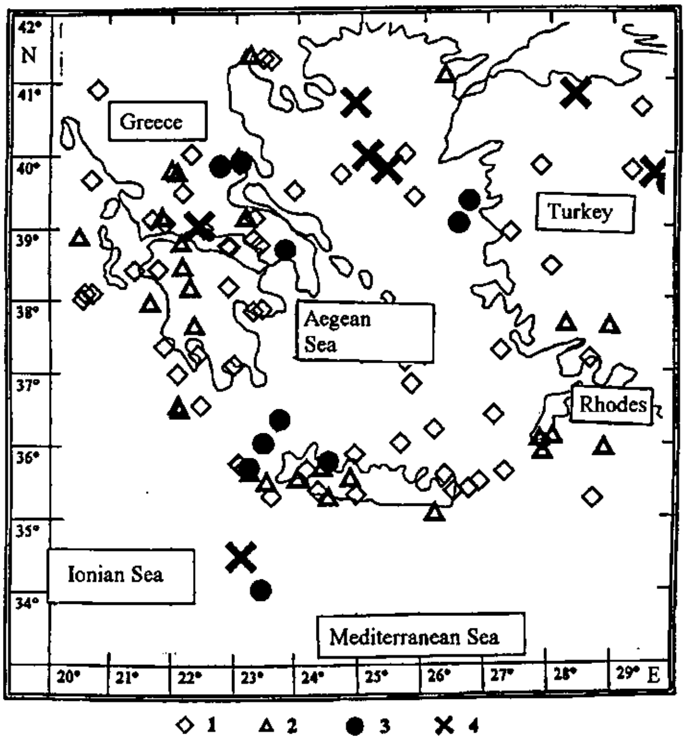


**Fig. 1**

Map showing epicenters of earthquakes of different magnitudes in Aegean region: (*1*) $4.0 < Mw < 4.9$; (*2*) $5.0 < Mw < 5.5$; (*3*) $5.6 < Mw < 5.9$; (*4*) $6.0 < Mw < 6.5$.

Figure 2 demonstrates source mechanisms of the strongest earthquakes in the 1964–1990 period. Data on the orientation of faults emerging to the surface are taken from different publications [8–10]. The type of stresses characteristic of various structures in the region can be deduced from the earthquake source mechanisms. For example, compressive stresses are typical of the southwestern part of the Hellenic arc, whereas its southeastern part and the territory of western Turkey are characterized by tensile stresses. The earthquake source mechanisms associated with the structures of the North Anatolian fault and its continuation in the northern area of the Aegean Sea are a right-lateral fault with an extension axis oriented roughly in a north-south direction.

## COMPUTATION RESULTS

The study region was divided into separate seismogenic volumes corresponding to $1° \times 1°$ surface sections. The average thickness of a seismogenic volume was taken to be 20 km. The average modulus of natural elasticity in the medium was assumed $\mu = 3 \times 10^{10}$ N m$^2$. The observations are of different degrees of representativity: the most reliable results were obtained for areas in eastern Greece, the Hellinic arc and western Turkey.

Computations have confirmed that tensile strain is predominant in this region. Extension is typical of most areas in the Aegean Sea, northeastern Greece, western portion of the Crete Island and western Turkey. Figure 3 presents orientation of the principal axes of tensile and compressive strain as projected on the Earth's surface over all elements of the structure. It can be seen that tensile strain is oriented roughly east-west in the southwestern part of Turkey and in an almost north-south direction in the areas of northwestern Turkey and western Greece. The southern part of the Aegean Sea is an almost aseismic, quasi-homogeneous and expanding structure. The bordering territories of Peloponnesus and southwestern Turkey seem to be pulled apart. Interestingly, the western half of the Crete Island undergoes tensile strain

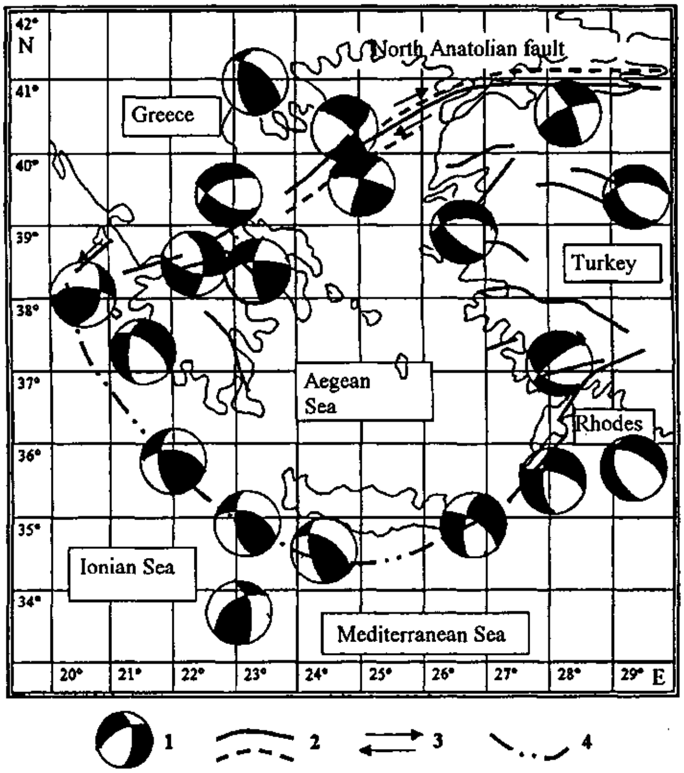


**Fig. 2**

(*1*) Source mechanisms of strongest earthquakes; (*2*) faults emerging to surface; (*3*) displacements over faults, and (*4*) Hellenic arc strike.

both horizontally and vertically, whereas its eastern portion is characterized by compressive strain in depth directed east-west.

Compressive strain prevails in the areas of the outer part of the Hellinic arc, on the Ionian Sea coast, westward and eastward of Crete. Here, the principal compressive and tensile strain axes have a rather similar orientation which is evidence of a vertical displacement at the boundaries of blocks corresponding to these structures. Compression both on a horizontal and a vertical plane was observed in the eastern part of Peloponnesus, near the Rhodes Island and also in the Mediterranean Sea, southwest of Crete. The principal compressive strain axis as projected on the Earth's surface in the Hellinic arc area and is oriented 12° northeast for the entire region.

In the northern Aegean Sea, areas of eastern Greece and northwestern Turkey the compressive and tensile strain axes are almost orthogonal to each other which characterizes predominant strike-slip motion at the boundaries of respective volumes. In the area of the Gulf of Corinth in Greece, extension vertically and in a north-south direction is accompanied by compression in the east-west direction. In the Peloponnesus territory, vertical and east-to-west compression is accompanied with extension directed from northwest to southeast.

Figure 4 is a map showing distribution of the effective strain rate on the basis of observations in the 1964–1990 period. These results have been obtained by the authors for the first time. The area of the maximum effective strain rate equal to $7 \times 10^{-7}$ year$^{-1}$ is situated in the eastern part of the Gulf of Corinth. Intensive strains were also observed in the outer part of the Hellinic arc and the northern Aegean area. Weak strain areas are located in the eastern part of Crete, near the eastern coast of Greece and in southwestern Turkey. The minimum strain rate ($8 \times 10^{-10}$ year$^{-1}$) was obtained for the area eastward of the Crete Island where a strong earthquake occurred on May 23, 1994. Figure 4 shows also the epicenters of earthquakes of magnitude over 6.0 that took place in the study region in the period from 1991 to 1997 included. Data on these earthquakes are presented in Table 1.

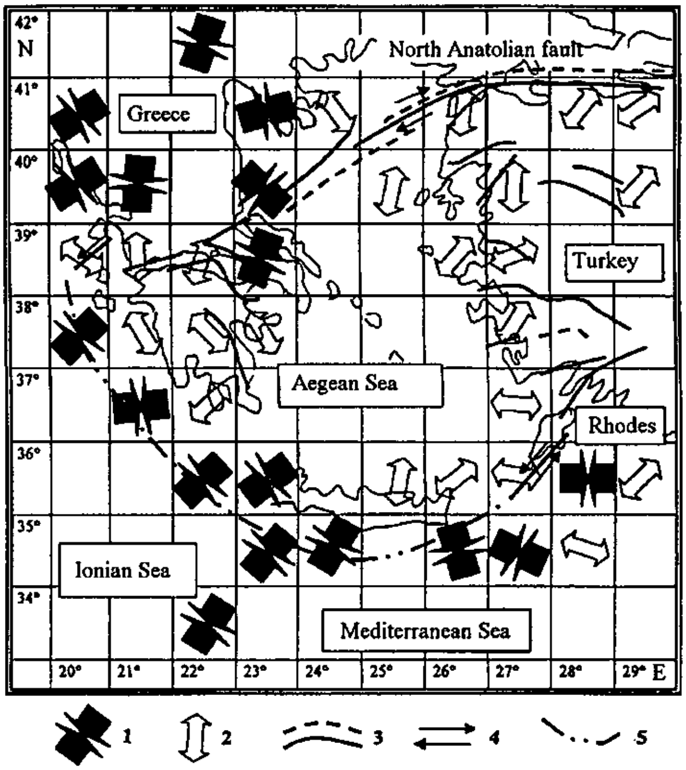


**Fig. 3**

Orientation of principal strain axes: (*1*) compressive; (*2*) tensile; (*3*) strike of main faults; (*4*) their displacement; (*5*) strike of Hellenic arc.

**Table 1**

| Date | Source coordinates | | | Magnitude, *Mw* | Earthquake region |
|---|---|---|---|---|---|
| | latitude (° N) | longitude (° E) | depth (km) | | |
| 06.11.1992 | 37.84 | 26.98 | 24.5 | 6.0 | Aegean Sea |
| 23.05.1994 | 35.02 | 24.89 | 80.8 | 6.1 | Crete Island |
| 13.05.1995 | 39.89 | 21.90 | 15 | 6.5 | Greece |
| 15.06.1995 | 38.10 | 22.46 | 15 | 6.5 | Greece |
| 01.10.1995 | 38.06 | 29.68 | 15 | 6.4 | Turkey |
| 20.07.1996 | 36.07 | 26.92 | 15 | 6.2 | Dodecanese Islands |
| 13.10.1997 | 36.10 | 22.04 | 44.2 | 6.4 | Southern Greece |
| 18.11.1997 | 37.33 | 20.84 | 22.9 | 6.6 | Ionian Sea |

The epicenters of the strongest earthquakes in the region (see Table 1) are located in the areas of minimum effective strain. The strongest earthquake occurred on November 18, 1997 in the area of the outer part of the Hellinic arc (Ionian Sea). Its epicenter is located in the area where effective strain is two orders of magnitude lower than the maximum strain. The earthquakes on October 1, 1995 and October 13, 1997 on the southwestern coast of Turkey occurred in regions where strains were below our determination level. An exception is the earthquake in the Gulf of Corinth which requires additional studies.

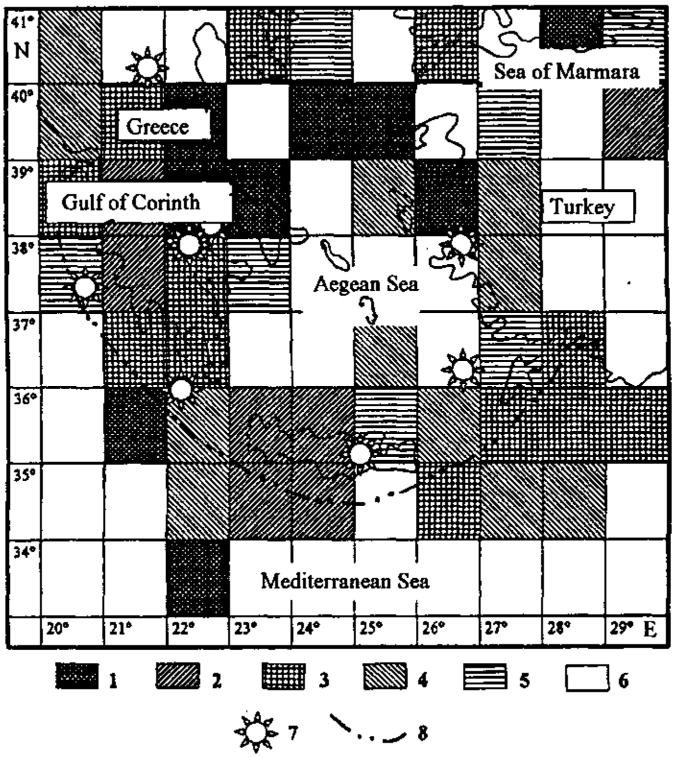


**Fig. 4**

Theoretical distribution of seismotectonic strain effective rate $\dot{\varepsilon}$ in 1964–1990 and epicenters of strongest earthquakes of 1991–1997: (*1*) $\dot{\varepsilon} \geq 5\times10^{-7}$; (*2*) $10^{-7} \leq \dot{\varepsilon} \leq 5\times10^{-7}$; (*3*) $10^{-8} \leq \dot{\varepsilon} \leq 10^{-7}$; (*4*) $10^{-9} \leq \dot{\varepsilon} \leq 10^{-8}$; (*5*) $10^{-10} \leq \dot{\varepsilon} \leq 10^{-9}$; (*6*) $\dot{\varepsilon} \leq 10^{-10}$; (*7*) sources of 1991–1997 earthquakes; (*8*) Hellenic arc strike.

## CONCLUSION

The studies we have performed are the first to demonstrate that the dominant strain process in the Aegean region is tensile strain. This type of strain is characteristic of most areas of the Aegean Sea, including the Crete basin, central Greece and western Turkey. In the southern part of the Aegean Sea, strain is oriented in an east-west direction so that the Peloponnesus and western Turkey structures seem to be pulled apart. As a result, the Earth's surface of the Crete Island is compressed in its western part and expanded in the eastern part of the island.

In the study period, the main tectonic process responsible for the strain of the Aegean region is displacement of the blocks along the North Anatolian fault and its continuation in the northern part of the Aegean Sea. This conclusion differs from the common view that geodynamics of this region is determined by interaction of the African plate with the continental margin of Europe in the Aegean arc area.

The epicenters of most of the strong earthquakes in the 1991–1997 period are located in the areas of the minimum effective strain rate. It can thus be asserted that the areas of the minimum values of the seismotectonic strain rate are those of high seismic hazard. This parameter of the strain process can be used as a promising characteristic for predicting the place of a possible strong earthquake.

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