Tectonophysics, 124 (1986) 55–66
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

RATES OF CRUSTAL DEFORMATION IN THE GULF OF CORINTH (CENTRAL GREECE) AS DETERMINED FROM SEISMICITY

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(Received April 26, 1985; revised version accepted September 4, 1985)

ABSTRACT

Tselentis, G.-A. and Makropoulos, K.C., 1986. Rates of crustal deformation in the Gulf of Corinth (central Greece) as determined from seismicity. *Tectonophysics*, 124: 55–66.

Seismic moment values and fault plane solutions for large ($M_s \geqslant 5.5$) earthquakes which occurred in the Gulf of Corinth (central Greece) over the last 25 years, were used to calculate the average rate of deformation in the area. The results show north–south and east–west extension together with a downward movement of the northern side of the Gulf relative to the south at about 1 mm/yr.

INTRODUCTION

The seismic moment tensor $\overline{M}$ is the most direct measure of the deformation associated with earthquakes. The moment tensor $\overline{M}$ can be described when the strike, dip and rake (or the plunge and trend of the *C*-axis) of the fault are known in addition to the scalar value M_0.

In the present study, the seismic moment of earthquakes with $M_s \geqslant 5.5$ which occurred after 1960 in the Gulf of Corinth area, are evaluated and Molnar's (1983) formula relating seismic moment to strain is used to calculate the amount of strain rate deformation resulting from slip during earthquakes over the above period.

TECTONIC SETTING AND SEISMICITY

The Gulf of Corinth (Fig. 1) occupies a zone of crustal extension which is an integral part of the Aegean Orogene and has long been recognised as a graben structure formed by normal faulting. Its western segment is connected to the Ionian trench system by a series of NE-trending transform faults with dextral polarity. The rift's eastern segment traverses the volcanic arc of the Aegean orogene and can be considered a first order cross fault. Extension is NNW–SSE in the eastern and NNE–SSW in the western part.

The variation in the stress direction indicates that two different tectonic processes control the evolution of the Corinth rift. The first involves westward obduction of

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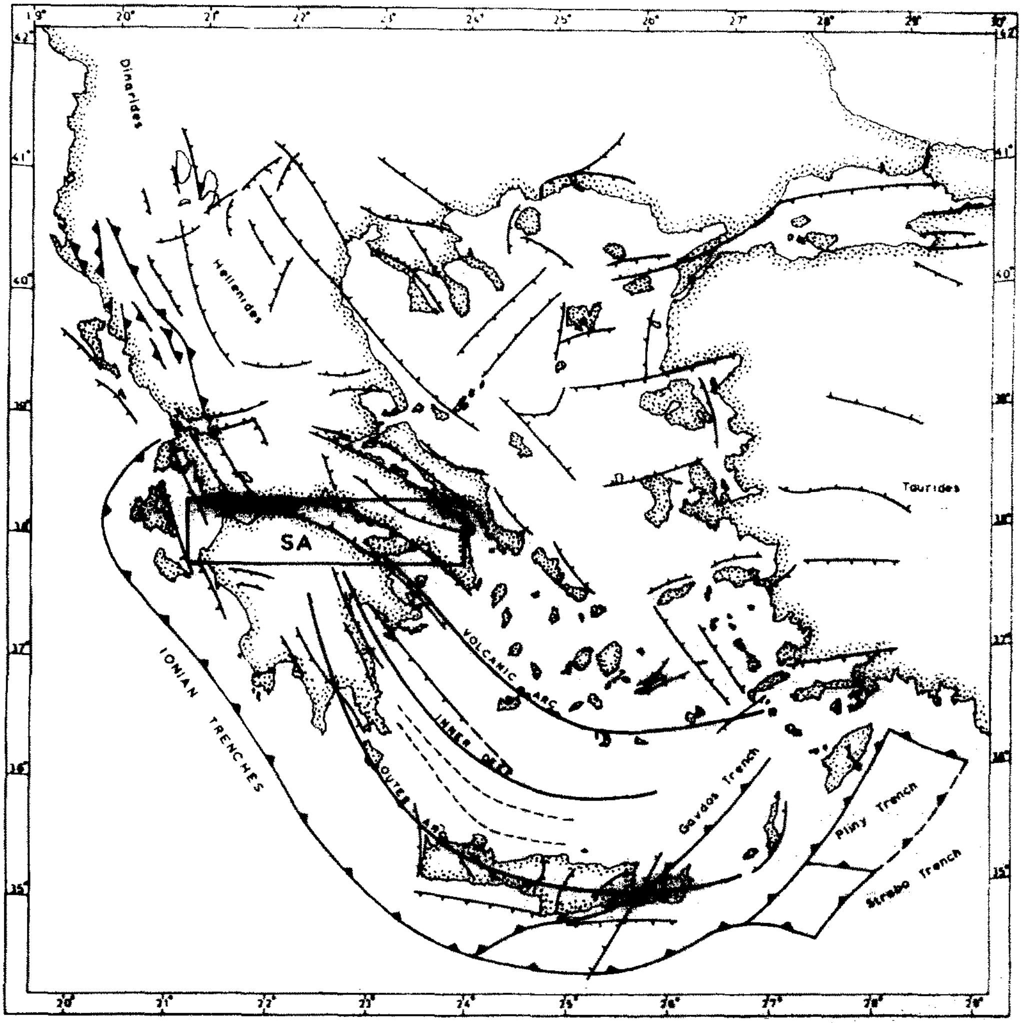

Fig. 1. Main tectonic features of Greece (from Drakopoulos and Makropoulos, 1983). SA: Study area.

the Peloponnesos with a clockwise rotation which is primarily responsible for the NNE–SSW extension in the western segment of the Gulf. This explains the divergence of the coast line and eastward widening of the Gulf. The second process controlling the tectonics of the Corinth rift is related to crustal arching along an axis trending roughly E–W. Vertical movement is restricted mainly to a relatively narrow crustal zone and has resulted in northward and southward tilting. In the eastern segment of the rift the E–W faults curve gently northeastward, or are offset en-echelon to facilitate release of the NNW–SSE stresses (Drakopoulos and Tilford 1981).

The Gulf of Corinth has long been known as a region of pronounced seismicity, with expected maximum earthquake magnitude $M_s = 7.2$ (Drakopoulos and

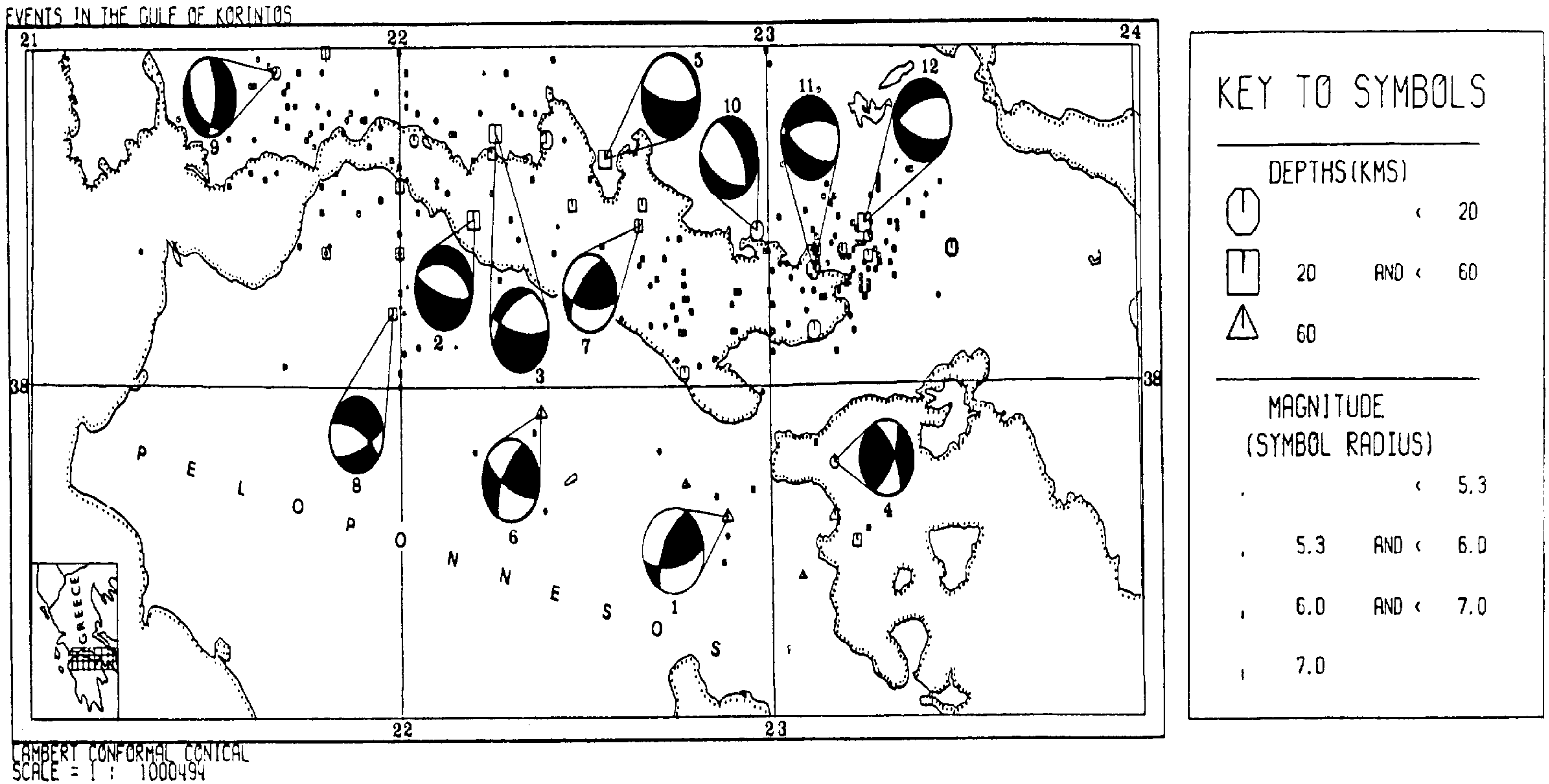

Fig. 2. Events in the Gulf of Corinth region since 1900 and earthquake mechanisms of large events ($M_s \geq 5.5$), since 1960, which were used in the present study.

Makropoulos, 1983; Makropoulos and Burton, 1985). Figure 2 shows all earthquakes which occurred in the area since 1900—taken from Makropoulos and Burton (1981) and the monthly bulletins of the National Observatory of Athens, together with the fault plane solutions of the larger shocks ($M_s \geqslant 5.5$) which occurred since 1960—taken from Drakopoulos and Delibasis (1983). From this figure one can deduce that most of the focal mechanisms indicate extension with stresses trending north–south.

THEORETICAL CONSIDERATIONS

The seismic moment tensor for a hypothetical shear dislocation at a point may be expressed as:

$$\boldsymbol{M}_{ij} = M_0(\boldsymbol{s}_i \boldsymbol{n}_j + \boldsymbol{s}_j \boldsymbol{n}_i) \qquad i,\ j = 1, 2, 3 \tag{1}$$

where M_0 is the scalar moment value and $\boldsymbol{s}$ and $\boldsymbol{n}$ are unit vectors (Fig. 3), in the direction of slip and normal to the fault plane, respectively (e.g. Aki and Richards, 1980).

The principal axes of $\boldsymbol{M}_{ij}$ are the P, T, and B axes. It must be noted however, that these axes when obtained from a single fault plane solution may vary significantly from the principal stress directions (McKenzie, 1969; Raleigh et al., 1972). In

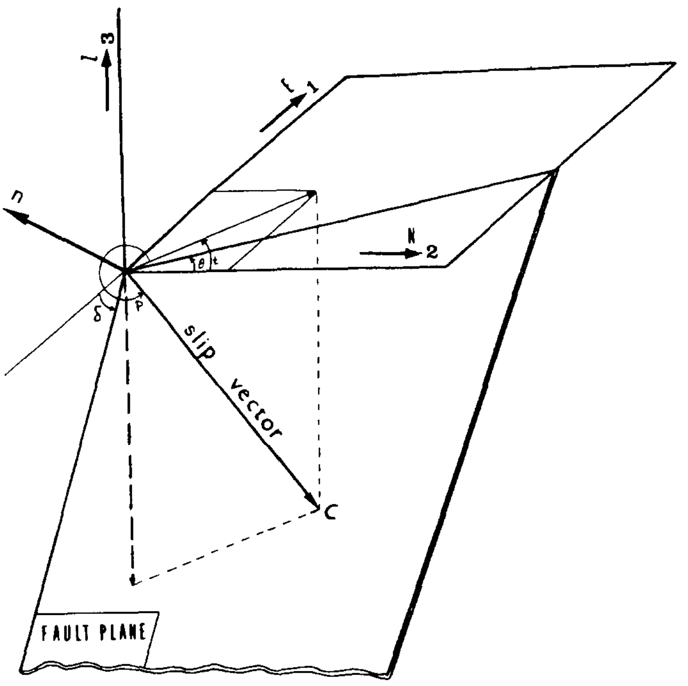

Fig. 3. Schematic diagram of fault geometry.

a body of rock under stress, slip can occur on pre-existing zones of weakness in a variety of orientations relative to the principal stresses. This means that a fault plane which coincides with a zone of weakness may bear no simple geometric relation to the stress directions by which it might be inferred.

If we are to estimate the displacement across a broad zone of deformation, we must sum the effects of slip on faults of different orientations. Brune (1968) and Kostrov (1974), developed methods for summing the seismic moments of many earthquakes to estimate the cumulative slip on a fault or the strain in a region where earthquakes have occurred.

Kostrov (1974), showed that the average rate of irrotational strain $[\dot{e}_{ij} = \frac{1}{2}(\partial u_i/\partial x_j + \partial u_j/\partial x_i)]$ in a volume due to discrete slips on different earthquake faults within the volume is:

$$\dot{e}_{ij} = \left(\sum_{1}^{N} \boldsymbol{M}_{ij} \right) / (2\mu VT) \tag{2}$$

where $\boldsymbol{M}_{ij}$ are summed over all N cuts in the seismogenic volume V of rigidity μ in time T, provided that the margins of the region considered are in the far field from each earthquake source.

Obviously the above formula is not applicable to the situation in which many faults of different orientations are active and intersect the boundaries of the region of interest. This happens in the present case.

Molnar (1983) presented a modification of Kostrov's formula to determine the average rate of finite (rotational) strain, ($\dot{e}^*_{ij} = \partial \dot{u}_i/\partial x_j$), for a region characterized by a set of faults irrespectively of their location and orientation:

$$\dot{e}^*_{ij} = \frac{1}{\mu VT} (\Sigma M^*_{ij}) \tag{3}$$

where $\Sigma \boldsymbol{M}^*_{ij}$ is the sum of asymmetric moment tensors:

$$\boldsymbol{M}^*_{ij} = M_0 \mathbf{b}_i \mathbf{n}_j \tag{4}$$

for earthquakes in the volume being considered. This approach is adopted throughout the present study.

Considering that axes *1*, *2*, *3* in Fig. 3 correspond to east, north and vertically upward directions respectively, we express the components of the asymmetric moment tensor in terms of parameters well known from the fault plane solutions.

In the above coordinate system, the fault normal n takes the form:

$$\begin{bmatrix} \sin \vartheta \sin \delta \\ \cos \vartheta \sin \delta \\ \cos \delta \end{bmatrix} \tag{5}$$

where ϑ is the strike of the fault plane in degrees east of north, δ is the dip of the fault plane.

In a similar way, the slip vector s takes the form:

$$\begin{bmatrix} \cos p \sin t \\ \cos p \cos t \\ \sin p \end{bmatrix} \tag{6}$$

where p is the plunge and t is the trend of the C-axis, both known as the fault plane solutions.

From (4), (5) and (6) the asymmetric moment tensor can be expressed as:

$$\begin{bmatrix} \cos p \sin t \sin \vartheta \sin \delta & \cos p \sin t \cos \vartheta \sin \delta & \cos p \sin t \cos \delta \\ \cos p \cos t \sin \vartheta \sin \delta & \cos p \cos t \cos \vartheta \sin \delta & \cos p \cos t \cos \delta \\ \sin p \sin \vartheta \sin \delta & \sin p \cos \vartheta \sin \delta & \sin p \cos \delta \end{bmatrix} \cdot M_0 \tag{7}$$

COMPUTATIONS AND RESULTS

With the assumed fault plane solutions and the seismic moment values calculated from a seismic moment–magnitude relation of the form:

$$\log M_0 = 18.27 + 1.15 M_s \tag{8}$$

which was developed for earthquakes in the area of Greece (Makropoulos and Latousakis, 1985), the sum of the asymmetric moment tensor becomes:

$$\sum_1^n M_{ij}^* = \begin{bmatrix} 4.6 & 2.3 & 5.1 \\ 4.6 & 3.4 & 8.7 \\ 16.3 & 4.4 & 9.2 \end{bmatrix} \times 10^{25} \text{ dyn cm} \tag{9}$$

Considering the dimensions of the deformed volume in north–south and east–west directions to be 100 km and 300 km respectively and assuming a thickness of the seismogenic volume for the region to be placed at 100 km, we calculate by using eqn. (4) the following strain rate tensor ($\mu = 3 \times 10^{11}$ dyn/cm^2):

$$\dot{e}_{ij}^* = \begin{bmatrix} 2.4 & 1.2 & 2.7 \\ 2.4 & 1.8 & 4.6 \\ 8.6 & 2.3 & 4.8 \end{bmatrix} \times 10^{-9}/yr \tag{10}$$

The movement represented by each component of the strain tensor $\dot{e}_{ij}^*$ is shown for reference in Fig. 4. Multiplication of the components of the strain tensor by appropriate distance across the deforming region yields estimates of the components of crustal extension, contraction, and shear displacement (see Fig. 4).

The dominant mode of deformation of about 8.6×10^{-9}/yr is expressed by the $\dot{e}_{31}^*$ component of the strain rate tensor and indicates a downward movement of the northern side of the region relative to the south. This result corresponds to about 1 mm/yr and is well in agreement with similar results obtained from geological investigations in the area (Kelletat et al., 1976; Mariolakos, 1976).

The results obtained indicate also north–south extension ($\dot{e}_{11}^* = 2.4 \times 10^{-9}$/yr) and east–west extension ($\dot{e}_{22}^* = 1.8 \times 10^{-9}$/yr) corresponding to 0.3 mm/yr and 0.6 mm/yr respectively.

TABLE 1

Date, location, fault parameters and seismic moments of events used

No.	Date (y-m-d)	Time (h.m.s)	Magn.. M_s	Depth (km)	Coordinates (°N)	Coordinates (°E)	C-axis plng.	C-axis trnd.	Strike (°)	Dip (°)	Moment (dyne cm × 10^{24})
1	1962-08-28	10:59:55	6.6	95	37.80	22.90	35	133	76	40	72
2	1965-03-31	09:47:29	6.6	45	38.30	22.20	88	174	101	89	72
3	1965-07-06	03:18:45	6.4	18	38.40	22.40	80	140	94	82	43
4	1968-07-04	21:47:54	5.6	20	37.80	23.20	27	74	117	37	4
5	1970-04-08	13:50:28	6.2	23	38.34	22.56	47	231	88	79	25
6	1972-09-13	04:13:20	6.2	75	38.00	22.40	46	33	52	80	25
7	1975-01-08	19:32:34	5.7	26	38.20	22.60	67	129	99	78	7
8	1975-04-04	05:16:16	5.7	56	38.10	22.00	40	312	103	60	7
9	1975-12-21	16:07:51	5.5	2	38.47	21.70	36	36	172	46	4
10	1981-02-24	20:53:36	6.6	10	38.10	23.00	40	19	64	70	72
11	1981-02-25	02:36:53	6.3	8	38.03	23.10	35	359	46	45	33
12	1981-03-04	21:58:07	6.4	8	38.24	23.26	20	16	55	30	43

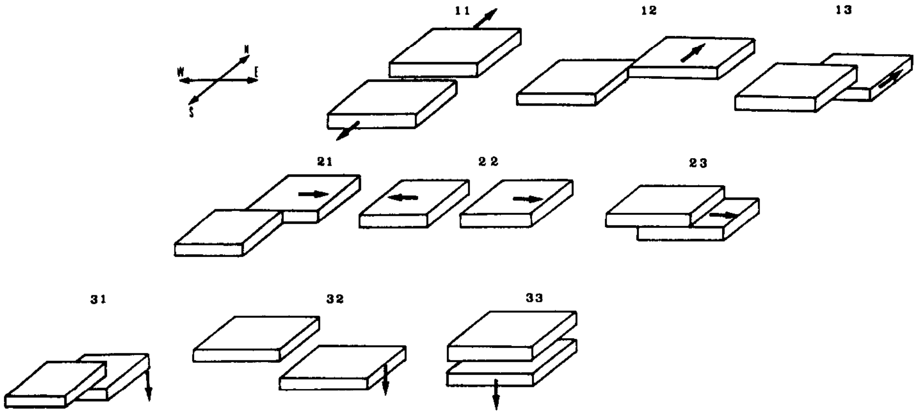

Fig. 4. Graphical representation of the strain tensor parameters.

The accuracy of the results may be affected by the small time interval considered, the effect of ignoring smaller earthquakes and errors in estimating seismic moment from eqn. (8).

Effect of nonstationarity of seismicity

Clearly, the recurrence rate of very large shocks has a large effect on the estimated average rate of deformation, and obviously the level of seismicity at the area during the last 25 years is not necessarily representative of a longer average. In fact 36% of the cumulative seismic moment was released in 1981 (Table 1).

Effect of incorrect calculation of seismic moment

Errors in calculating seismic moments involve errors in the calculation of the scalar value of the seismic moment tensor by using eqn. (8) and errors in the calculation of the components of the tensor due to incorrect determined fault-plane solutions of the events considered.

Effect of small earthquakes

The contribution of small events can be estimated from the frequency–magnitude ($\log N = a - bm$) and magnitude moment ($\log M_0 = A + Bm$) relations as follows: The annual moment release for earthquakes with magnitude in the range $\mathrm{d}m$ is:

$$\mathrm{d}M_0 = 10^{A+Bm} \times b \times 10^{a-bm} \tag{11}$$

thus, the total annual moment release for earthquakes with magnitude between m_1 and m_2 is:

$$M_0 = b \times \int_{m_1}^{m_2} 10^{A+Bm} \times 10^{a-bm} \times \mathrm{d}m = \frac{b}{B-b} \times 10^{A+a}\left[10^{(B-b)m_2} \times 10^{(B-b)m_1}\right] \tag{12}$$

thus, only 4% of the moment release corresponds to events with magnitudes less than those ($M_s \geqslant 5.5$), considered in the present analysis.

CONCLUSION

The rate of seismic moment release calculated from recent seismicity data in the area of Gulf of Corinth (central Greece) allowed the calculation of crustal deformation rates. The pattern of deformation caused by the seismic slips show a north-south and east-west extension at 0.3 and 0.6 mm/yr respectively together with a downwards movement of the northern side of the Gulf relative to the south at about 1 mm/yr. Although estimates of deformation rates for such a small period are susceptible to errors, the general trend of the results obtained is well in agreement with similar results obtained from other investigations in the area.

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