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AVERAGE REGIONAL SEISMIC STRAIN RELEASE RATES IN THE PATRAHIKOS-SARONIKOS GULFS (CENTRAL GREECE) BASED ON HISTORICAL INSTRUMENTAL DATA

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A B S T R A C T

The seismic moment release in the area of Patrahikos to Saronikos Gulfs (Central Greece) is determined on the basis of the earthquakes which occurred over a period of about 240 years (1748-1985) and have magnitudes $M_S \geq 6.2$. This time period is considerably longer than the average return period of large earthquakes in this region (~35 years). The moment release rate ($0.48\ 10^{25}$ dyn cm yr^{-1}) is then used to calculate the average seismic strain rate in the whole area which was found equal to $6.1\ 10^{-8}\ yr^{-1}$. Moment tensor analysis of 7 earthquakes of the period 1965-1981 revealed that the strain accumulation in the area is mainly taken up by north - south extension and vertical movement. These results are in agreement with the regional stress field.

Σ Υ Ν Ο Ψ Η

Δίδεται ερμηνεία του ρυθμού έκλυσης της σεισμικής ροπής στη περιοχή μεταξύ των μεσημβρινών 21.5°-23.7°E και των παραλλήλων 37.7°N-38.5°N που καλύπτουν τον Πατραϊκό, Κορινθιακό και Σαρωνικό Κόλπο. Το κύριο αντικείμενο είναι η ερμηνεία στη σχέση μεταξύ της συχνότητας της γένεσης των σεισμών και τον ρυθμό της παραμόρφωσης σε μια περιοχή με πολλά ρήγματα. Ο τελευταίος σεισμός στον Πατραϊκό Κόλπο έγινε το 1858 (M_S= 6.8) και η πιθανότητα γένεσης ενός μεγαλύτερου σεισμού στα επόμενα 20 χρόνια είναι πολύ υψηλή.

Β.Κ.ΠΑΠΑΖΑΧΟΣ-Α.Α.ΚΥΡΑΤΖΗ-ΧΡ.Α.ΠΑΠΑΪΩΑΝΝΟΥ-Δ.Γ.ΠΑΝΑΓΙΩΤΟΠΟΥΛΟΣ
Ρυθμός παραμόρφωσης και εκλυσης σεισμικής ροπής στον Πατραϊκό-Σαρωνικό Κόλπο (Κεντρική Ελλάδα) με σεισμολογικά δεδομένα.

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Τα δεδομένα που χρησιμοποιήθηκαν για την ερμηνεία του ρυθμού παραμόρφωσης καλύπτουν μια περίοδο 240 ετών (1748-1985) με μεγέθη $M_S \geq 6.2$. Η περίοδος αυτή είναι αξιοσημείωτα μεγαλύτερη από τη μέση περίοδο επανάληψης των μεγάλων σεισμών σ' αυτήν την περιοχή (~ 35 έτη). Ο ρυθμός έκλυσης της σεισμικής ροπής για την περιοχή αυτή βρέθηκε ίσος με $0.48\ 10^{25}$dyn cm yr^{-1}. Κατόπιν ο ρυθμός παραμόρφωσης υπολογίστηκε και βρέθηκε ίσος με $6.1\ 10^{-8}\ yr^{-1}$. Θέλοντας να εξετάσουμε τον τρόπο παραμόρφωσης στην περιοχή υπολογίσαμε τις καρτεσιανές συνιστώσες του τανυστή ροπής από επτά σεισμούς με αξιόπιστους μηχανισμούς γένεσης. Βρέθηκε οτι η συσσώρευση της τάσης στη περιοχή οφείλεται κυρίως στην ύπαρξη N-S εφελκυσμού και κατακόρυφων κινήσεων. Τα αποτελέσματα είναι σε συμφωνία με το γενικό πεδίο των τάσεων στον ευρύτερο ελληνικό χώρο.

INTRODUCTION

The present pattern of active tectonics in the Aegean Sea and adjacent areas is mainly attributted to the interaction between the African and Eurasian lithospheric plates (Papazachos and Comninakis 1969, 1971). As a result of this collision, a number of tectonic features characterize the Aegean area (McKenzie 1972, 1978 Papazachos et al 1986) and any possible geodynamic model proposed has to interprete their existence.

In a previous paper (Papazachos et al 1987a), the Aegean area was divided into 19 so-called "fracture zones", along which the seismicity seems to be aligned. In order to identify these seismic fracture zones both historical and instrumental seismicity has been used. The data set was complete for earthquakes with magnitude $M_S \geq 6.2$ for the last three centuries, in average.

The abudant available data spanning a long period of time (both in historical and present seismicity) for most of these fracture zones, stimulate the interest to study the crustal deformation caused by earthquakes in the Aegean area. The problem is the relation between the frequency of occurrence of earthquakes and the rate of deformation of a region with many faults.

In the present paper, the area bounded between the meridians 21.5^oE-23.7^oE and the parallels 37.3^oN-38.5^oN, covered by the Patrahikos, Corinthiakos and Saronikos Gulfs, is studied. Similar study has already been performed by Tselentis and Makropoulos (1986) in the Corinthiakos Gulf using only data of the last 22 years.

The area of the Patrahikos-Corinthiakos Gulfs has been recognized as a predominantly assymetric graben with antithetic faulting on the northern side (Jackson et al 1982, Papazachos et al 1984, King et al 1985, Vita-Finzi and King 1985). The last large earthquake in the Patrahikos Gulf occurred in 1858 (M_S=6.8) and Papazachos et al (1987b) have assigned the area the highest probability for the occurrence of a strong event in the next 20 years. In 1981 a sequence occurred in the Corinthiakos Gulf with three shocks of magnitude, M_S, 6.7, 6.4 and 6.3. Finally, further east, in the Saronikos Gulf no earthquake with magnitude $M_S \geq 6.8$ has ever occurred and the last event occurred in 1928 (M_S=6.3) (Papazachos et al 1987b).

THE DATA

Three sources of data were used in the present study. The first was a catalogue of historical earthquakes covering the period 479 BC - 1900 AD (Papazachos and Comninakis 1982). The second source was an unpublished catalogue of historical earthquakes compiled over the last 10 years. The last source was the recently updated catalogue of instrumental data (Comninakis and Papazachos 1986) for the broader Aegean area.

All earthquakes with $M_S \geq 6.2$ (threshold for data completeness of historical events) and $M_S \geq 6.0$ (threshold for the present century seismicity), which have occurred in the area of Patrahikos - Corinthiakos - Saronikos Gulfs over a period of 240 years (1748-1985) were depicted from the above mentioned catalogues and are listed in table 1. The epicenters and the magnitudes of the historical earthquakes are estimated on the basis of the macroseismic information available for any one particular event. The epicenter represents the macroseismic epicenter with an estimated error of the order of 25Km. The area of study has been always very densely populated, both in historical times as well as in modern times. Thus there was abudant information concerning macroseismic damage reports for each event of the historical times. For each case the intensities were estimated , then the isoseismals were drawn and the macroseismic epicenter was determined. The magnitude for each event of the historical times was calculated using the following scaling relation proposed by Papaioannou (1984)

$$I=6.59+1.18M_S-4.50\log(D+17) \quad (1)$$

where D is the distance in Km. This scaling relation was calibrated using the most reliable isoseismals of the broader Aegean area of the period 1901-1984. The estimated uncertainties in the magnitude determination is no more than 0.4 of a magnitude unit.

Table 1. Information on all the strong main shocks occurred in the area of study during 1748-1985.
Πίνακας 1. Παράμετροι όλων των μεγάλων σεισμών την περίοδο 1748-1985 που έγιναν στην υπό μελέτη περιοχή.

N	Date	Epicentral Coordinates φ_N^o	λ_E^o	M_s	M_o ($*10^{25}$ dyn·cm)	Maximum Intensity
1	1748, May 14	38.2	22.1	6.6	4.42	IX (Aeghio)
2	1753, Mar. 7	38.1	21.6	6.2	1.45	VIII (Zacholi)
3	1785, Jan. 30	38.2	21.7	6.6	4.42	IX (Patras)
4	1804, June 8	38.2	21.8	6.7	5.85	IX (Patras)
5	1806,	38.2	21.9	6.3	1.92	VIII (Patras)
6	1817, Aug. 23	38.3	22.0	6.9	10.21	X (Aeghio)
7	1837, Mar. 20	37.4	23.6	6.2	1.45	VII (Hydra)
8	1858, Feb. 21	37.9	22.9	6.8	7.73	X (Corinth)
9	1861, Dec. 26	38.2	22.3	6.8	7.73	XI (Valymitica)
10	1870, Aug. 1	38.4	22.6	7.0	13.49	X (Itea)
11	1876, June 26	37.8	22.8	6.2	1.45	VIII (Nemea)
12	1887, Oct. 3	38.0	22.7	6.2	1.45	VIII (Xylokastro)
13	1888, Sep. 9	38.1	22.1	6.4	2.54	IX (Valymitica)
14	1889, Aug. 25	38.3	22.1	6.5	3.35	VIII (Fteri)
15	1909, May 30	38.4	22.2	6.2	1.45	VIII (Dafnochori)
16	1917, Dec. 24	38.4	21.8	6.0	0.83	VIII (Naupaktos)
17	1928, Apr. 22	37.9	23.0	6.3	1.92	IX (Corithos)
18	1930, Apr. 17	37.8	23.1	6.0	0.83	VIII (Sofiko)
19	1965, July 6	38.4	22.4	6.3	1.92	VIII+ (Eratini)
20	1970, Apr. 8	38.3	22.6	6.2	1.45	VII (Antikyra)
21	1981, Feb. 24	38.2	23.0	6.7	5.85	IX (Perachora)

Table 1 lists information on all the main shocks which have occurred in the area with magnitude $M_S \geq 6.2$, for a time period of 240 years, namely 1748-1985. All events used in this study are shallow ($h \leq 15$Km). The seismic moments listed in table 1 were calculated from a scaling relation (Kiratzi et al 1985).

Figure 1 shows the epicenters listed in table 1. Black squa-

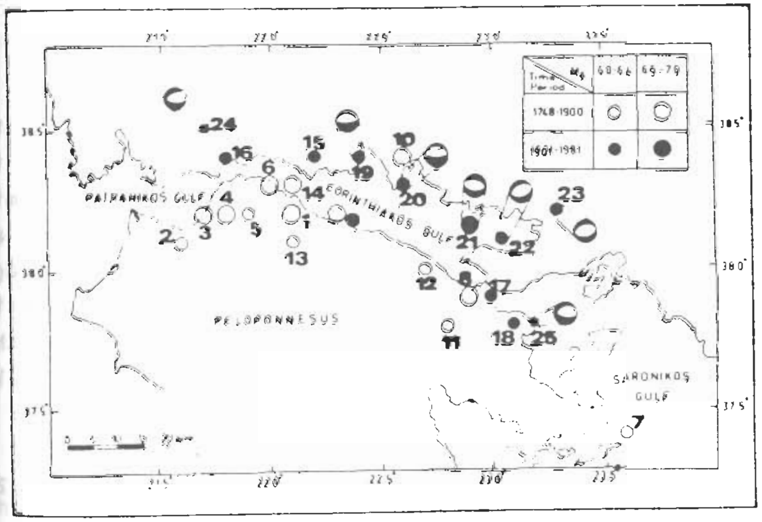

Fig. 1. Geographical distribution of the epicenters of the historical earthquakes with $M_S \geq 6.2$ and of the instrumental seismicity with $M_S \geq 6.0$. Open circles stand for the historical events, while black circles represent events of the present century. Black squares correspond to two earthquakes of the present century, with $M_S < 6.0$, of which only the focal mechanisms were used. The available fault plane solutions for seven earthquakes of the period 1965-1981 are also shown. Numbers 1-21 correspond to table 1.

Σχ. 1. Γεωγραφική κατανομή των επικέντρων των ιστορικών σεισμών με $M_S \geq 6.2$ και της ενόργανης σεισμολογίας με $M_S \geq 6.0$. Ανοιχτοί κύκλοι δείχνουν τους ιστορικούς σεισμούς ενώ οι μαύροι κύκλοι παρουσιάζουν τους σεισμούς του παρόντα αιώνα. Μαύρα τετράγωνα αντιστοιχούν σε δύο σεισμούς του παρόντα αιώνα με $M_S < 6.0$ των οποίων οι μηχανισμοί γένεσης χρησιμοποιήθηκαν. Επίσης δείχνονται οι διαθέσιμοι μηχανισμοί γένεσης για επτά σεισμούς της περιόδου 1965-1981. Τα νούμερα 1-21 αντιστοιχούν στον πίνακα 1.

res (events no. 24, 25) correspond to two earthquakes of the present century with magnitudes less than 6.0, which are not included in table 1. Also not included in table 1 are the aftershocks of the 1981 Corinth earthquake marked with numbers 22 and 23. It is observed that in the present century the seismicity was restricted in the northern part of the area. In the same figure the available fault plane solutions for 7 earthquakes are shown, which are all based on long period first motions. The mechanisms of the 19, 20, 24 events are determined by McKenzie (1972, 1978), the one of the 25 event by Ritsema (1974) and those of the 21, 22 and 23 events by Papazachos et al (1984).

ESTIMATION OF THE SEISMIC MOMENT RELEASE RATE

In order to calculate the seismic moment release in the area, we followed a methodology by Molnar (1979). According to it, the frequency of occurrence of earthquakes with different seismic moments is expressed in terms of the rate of slip on a fault and to the largest seismic moment likely to occur in the region. Beginning from the Gutenberg-Richter empirical expression relating recurrence of events with different magnitudes and using another empirical relation between magnitude and seismic moment, the relative number of events with seismic moment greater or equal to M_0 is given by

$$N(M_0) = A\, M_0^{-B} \tag{2}$$

with

$$A = 10^{\left(a+\frac{bd}{c}\right)} \quad \text{and} \quad B = \frac{b}{c} \tag{3}$$

where a,b are the constants from the Gutenberg-Richter relation and c, d the constants of the empirical moment-magnitude relation. The rate of occurrence of seismic moment, $\dot{M}_0^{\Sigma}$, is given by

$$\dot{M}_0^{\Sigma} = \frac{A}{1-B}\, M_{0_{max}}^{(1-B)} \tag{4}$$

where $M_{0_{max}}$ is the maximum possible seismic moment in the region, which in our case is equal to $13.49 \cdot 10^{25}$ dyn cm (event of August 1, 1870, Papazachos and Comninakis 1982). The values of c and d are equal to 1.21 and 17.66, respectively (Kiratzi et al 1985). Equation 4 is valid if B<1 and if B≠1 (Molnar 1979).

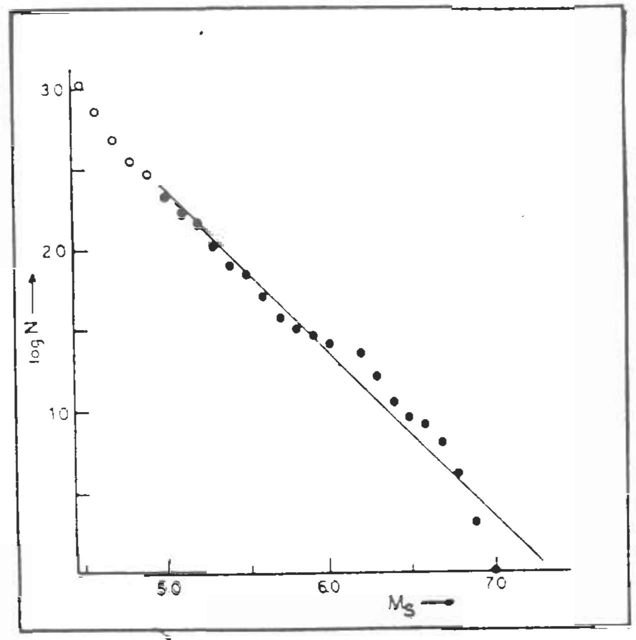

Fig. 2. Plot of the logarithm of the cumulative normalized frequency of shocks, versus magnitude. Black circles correspond to the complete data set of the area of study, for events with $M_S \geq 5.0$. The slope of the solid line was found equal to 0.99.

Σχ. 2. Λογάριθμος της συσσωρευτικής εξομαλυμένης συχνότητας των σεισμών σε σχέση με το μέγεθος. Μαύροι κύκλοι αντιστοιχούν σε πλήρη δεδομένα της υπομελέτη περιοχής για σεισμούς με $M_S \geq 5.0$. Η κλίση της συνεχής γραμμής βρέθηκε ίση με 0.99.

Figure 2 represents the frequency magnitude relation for the earthquakes of the area of study. In this plot, data of smaller events occurred in the area during the present century are also included. The straight line, which has been determined by least squares and fits the observations with $M_S \geq 5.0$, has the equation

$$\log N = 7.28 \pm 0.27 - (0.99 \pm 0.04) M_S \tag{5}$$

where 0.99 is the b value while the corresponding a value normalized to 1 year is equal to 4.90.

For each sucessive year of an earthquake occurrence (data of table 1) the moment release rate, as determined by equation 4, was multiplied by the years elapsed since the previous event. This incremental moment release rate was plotted versus the incremental time. This plot revealed that the incremental moment release rate was steady with a mean of 4.76 10^{24} dyn cm yr^{-1} and a standard deviation equal to 0.73 10^{24} dyn cm yr^{-1}.

In figure 3 the cummulative seismic moment is plotted

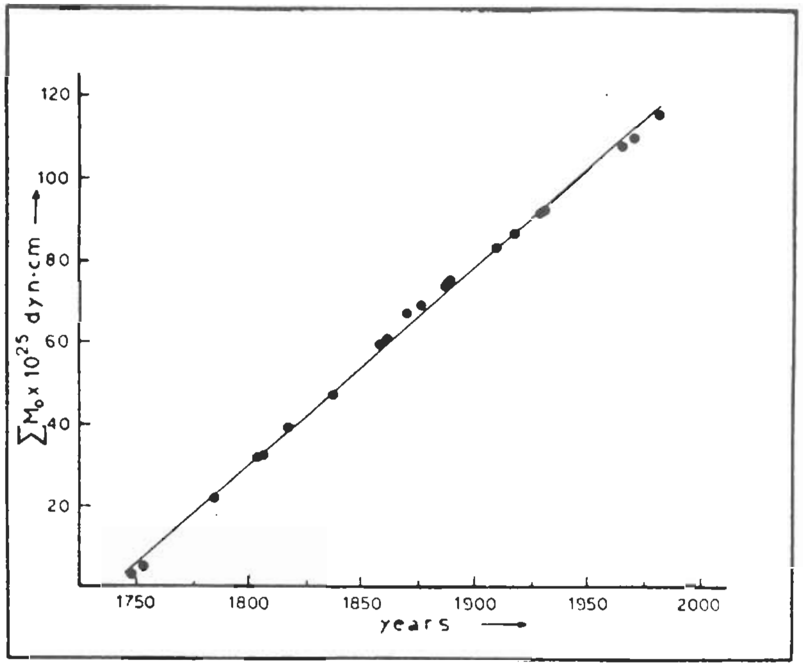

Fig. 3. Plot of the cumulative seismic moment of the strongest earthquakes, versus magnitude for the Patrahikos-Corinthiakos-Saronikos Gulfs area. The slope of the solid line was found equal to 0.48 10^{25} dyn cm yr^{-1}.

Σχ. 3. Συσσωρευτική σεισμική ροπή των μεγαλυτέρων σεισμών σε σχέση με το μέγεθος για τις περιοχές των Πατραϊκού-Κορινθιακού - Σαρωνικού Κόλπου. Η κλίση της συνεχούς γραμμής βρέθηκε ίση με 0.48 10^{25} dyn cm yr^{-1}.

versus time. It is clearly seen that the moment release in this region has been stable for about 240 years. The straight line determined by linear regression has a slope equal to 0.48 10^{25} dyn cm yr^{-1}, which is the rate of moment release by earthquakes in the area. The mean RMS value of the regression is 1.69 10^{25} dyn cm.

In order to examine any possible spatial variation of the moment rate, the zone was divided into 3 subregions covering the Patrahikos (38.1°N-38.5°N, 21.5°E-22.3°E), Corinthiakos (38.0°N-38.5°N 22.3°E-23.1°E) and Saronikos (37.3°N-38.0°N, 22.7°E-23.7°E), Gulfs respecively. Similar plots to the one shown in figure 2 were produced to determine the a and b values for eacn subregion. Equation

Table 2. Estimated moment rate values for each subregion

Πίνακας 2. Υπολογισμένες τιμές ρυθμού μεταβολής της Ροπής για κάθε υποπεριοχή.

Region	a	b	$M_{o\,max}$ ($*10^{25}$dyn·cm)	$\dot{M}_o^{\Sigma}$ ($*10^{25}$dyn·cm·yr^{-1})
Patrahikos Gulf	3.11	0.75	10.21	0.23
Corinthiakos Gulf	2.27	0.63	13.49	0.21
Saronikos Gulf	3.52	0.86	7.73	0.13

4 was used and the results are summarized in table 2. The moment rate, 0.48 10^{25} dyn cm yr^{-1}, determined for the whole area predicts that an earthquake of magnitude 5.9 is bound to occur every year.

AVERAGE REGIONAL SEISMIC STRAIN RATE

After seismic moment was recognized as the fundamental parameter that quantitavely describes the size of an earthquake, 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) considered a volume within which there is a spontaneous release of strain energy and the average deformation caused by one or many events is pure shear, with no net rotation. However, Brune (1968) was not concerned with a volume but with a plane of finite dimensions and considered only the slip that rotates one side of the fault past the other. Molnar (1983) modified Kostrov's , (1974) formula to determine the average rate of rotational strain resulting from faulting.

In the present study, Kostrov's (1974) formulation is followed to determine the strain rate $\dot{\varepsilon}$, since we have a volume and discrete slip on different earthquake faults within this volume. The strain rate $\dot{\varepsilon}$ is given by

$$\dot{\varepsilon} = \frac{\dot{M}_o^{\Sigma}}{2\mu V} \qquad (6)$$

where $\dot{M}_0^{\Sigma}$ is the moment rate, V is the volume and μ is the shear modulus ($=3\ 10^{11} dyn\ cm^{-2}$). In our case the volume of the whole area is equal to 171793 km^3, (Papazachos et al 1987b), assuming a depth of the seismogenic volume equal to 15Km. Aseismic strain is neglected in this study.

Obviously, this formula can only be used if the earthquakes involved have similar focal mechanism. Unfortunately, for this area we have only seven reliable fault plane solutions for earthquakes occurred after 1964. All for these solutions, as shown in figure 1, imply normal faulting with the T axis trending in an almost north-south direction. In this respect, equation 6 was used to

Table 3. Mean regional strain rates determined from eq. 6
Πίνακας 3. Μέσος ρυθμός παραμόρφωσης

Region	$\dot{\varepsilon}$ (yr^{-1})
Patrahikos Gulf	$7.93 * 10^{-8}$
Corinthiakos Gulf	$6.56 * 10^{-8}$
Saronikos Gulf	$3.13 * 10^{-8}$
Whole area	$(6.07\pm0.71) * 10^{-8}$

determine the average strain rates, due to earthquakes, in each area and the results are summarized in table 3.

It seems that the strain accumulation decreases by a factor of two as we go from west to east, namely from Pathrahikos to Saronikos Gulfs. Indeed the reccurrence times for earthquakes with $M_S \geq 6.5$ increase as we go from the western to the eastern parts of this area (Papazachos et al 1987b).

The uncertainties introduced to the estimation of the strain rates are estimated using equations 4 and 5 and the moment-magnitude relation assuming a 0.4 error to the magnitude. In this way, it was found that the magnitude uncertainty results in a $0.20\dot{\varepsilon}$ uncertainty of the strain rate.

Wishing to examine how the deformation is taken up in this region, we calculated the cartesian components of the moment tensor (Aki and Richards 1980) for the seven earthquakes with reliable fault plane solutions for the period 1965-1981. Kostrov (1974) suggested summing moments for a group of earthquakes sharing the same source mechanism in a given volume, which is the case in the present study, to find the total strain in the volume. In this case equation 6 takes the form

$$\dot{\varepsilon}_{ij} = \frac{\sum M_{ij}}{2\mu VT} = \frac{1}{2\mu V} \cdot \frac{\sum M_{ij}}{T} \qquad (7)$$

where $\sum M_{ij}$ is the sum of the moment tensor elements and T is the duration of the time considered.

The second term of the product is equivalent to the seismic moment tensor rate $\dot{M}_{ij}$ and thus equation 7 can be written in the form of

$$\dot{\varepsilon}_{ij} = \frac{1}{2\mu V} \dot{M}_{ij} \qquad (8)$$

With the 1 direction pointing north, the 2 direction pointing east and the 3 direction pointing down, the following cummulative seismic moment rate tensor was obtained

$$\dot{M}_{ij} = \begin{pmatrix} 0.28 & -0.09 & -0.12 \\ -0.09 & 0.10 & 0.08 \\ -0.12 & 0.08 & -0.38 \end{pmatrix} * 10^{25}\ dyn\cdot cm\cdot yr^{-1} \qquad (9)$$

The corresponding strain rate tensor e_{ij} has as follows,

$$\dot{\varepsilon}_{ij} = \begin{pmatrix} 2.72 & -0.87 & -1.16 \\ -0.87 & 0.97 & 0.78 \\ -1.16 & 0.78 & -3.69 \end{pmatrix} * 10^{-8}\ yr^{-1} \qquad (10)$$

The large values of M_{11} and M_{33} correspond to large values of extension in the north-south direction and contraction in the vertical direction.

The average rate of north-south extension 2.72 $10^{-8}\ yr^{-1}$ corresponds to a velocity extension of 0.14 cm yr^{-1} for a region with 50km width in the north south direction. The values of the moment rate and strain rate tensors show that the amount of contraction in the north-south and vertical directions are comparable. Therefore, if this tensor is proportional to the rate of change of the strain field for this area, then the north - south extension would be balanced by equal amounts of vertical motion (either uplift of subsidence). The values obtained here are of rather qualitative interest, since we cannot assign a sensible quantitative value to their uncertainties, nevertheless they are in a good agreement with the regional stress field characterizing the Aegean area (McKenzie 1978, Dewey and Sengör 1979, Papazachos et al 1983, 1986, Rotstein 1985).

CONCLUSIONS AND DISCUSSION

The rate of seismic moment release in the area of Patrahikos-Corinthiakos-Saronikos Gulfs was calculated on the basis of shallow historical and instrumental data covering the period 1748-1985. It was found that over 240 years the moment release in the area was remarkably stable with an average rate of 0.5 10^{25} dyn cm yr^{-1}. The average regional strain rate caused by earthquakes for this period of time was estimated to be equal to 6.1 $10^{-8} yr^{-1}$. Considering the length of the time spanned by the data (240years) we may conclude that this value reflects the general trend of deformation in this particular region.

The pattern of deformation caused by the seismic slip was further examined on the basis of the moment rate tensor and the strain rate tensor. As one would expect from the knowledge of the Aegean area, the analysis of the moment rate and strain rate tensors revealed that north-south extension (crustal thinning) and thus srbsidence are the dominant mode of deformation in the area of study. Recent geomorphological observations at the Corinthiakos Gulf (Vita-Finzi and King 1985) show evidence of subsidence and uplift (raised beaches). The uplift is presumably the formation of a saw tooth topography (caused by normal faulting) on a general subsidence (caused by extension and thinning).

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