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# Seismic moments of earthquakes at the western Hellenic arc and their application to the seismic hazard of the area

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**Abstract**

Tselentis, G.-A., Stavrakakis, G., Makropoulos, K., Latousakis, J. and Drakopoulos, J., 1988. Seismic moments of earthquakes at the western Hellenic arc and their application to the seismic hazard of the area. *Tectonophysics*, 148:73–82.

Seismic moments of 45 large earthquakes ($M_s \geqslant 5.2$) which occurred in the southwestern part of the Hellenic arc–trench system between 1950 and 1981 were used to express the frequency of occurrence of earthquakes in terms of the subduction rate, and the largest seismic moment likely to occur in the region.

For this purpose, a moment versus magnitude relationship for earthquakes characteristic of the region was derived, and the subduction rate was estimated from seismic moment rates.

## Introduction

The Hellenic arc–trench system is a subduction zone of about 1000 km, where the African lithosphere is subducting under the Aegean lithospheric plate in a roughly SW–NE direction. This motion of the Hellenic consuming boundary with respect to Africa results from three different processes, the northward motion of the African plate, the Aegean extensional spreading, and the westward motion of Turkey (McKenzie, 1970, 1978).

Many authors have attempted to obtain an estimate of the rate of underthrusting of the Mediterranean slab using various methods. Ryan et al. (1973) estimated a subduction rate of the order of 1.5 cm/yr on the basis of the rate of tilting of the turbiditic layers filling the arc.

McKenzie (1978) obtained a slip rate of 7 cm/yr based on the directions of the Turkey–Eurasia, Turkey–Aegean and Aegean–Africa slip vectors, and assuming 4 cm/yr slip rate at the North Anatolian plate boundary. This value should be regarded as overestimated by a factor of two if one takes into consideration a creep rate of 1–1.5 cm/yr at the North Anatolian at Izmet Paza (Aytum, 1980).

Le Pichon and Angelier (1979), who assumed that the subduction began 13.5 m.y. ago, obtained a slip rate of 2 cm/yr for the western part and 4.5 cm/yr for the eastern part of the Hellenic arc. As they pointed out, the difference is due to the rotation pole which is located relatively close to the boundary.

Recent developments in the theory of earthquake mechanism, most notably the concept of seismic moment, enable determinations of the extent to which interactions between plates affect the rates of seismicity along their boundaries.

The seismic moment proved to be the funda-

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mental parameter that describes the static aspects of earthquakes. Since the amplitude of ground motion is physically and directly related to the seismic moment, quantitative estimates of seismic hazard that include a deterministic prediction of ground motion must include the seismic moment as a parameter (Heaton and Helmberger 1978; Molnar 1979).

Molnar (1979) developed a formalism that relates the frequency of occurrence of earthquakes to the rate of slip on a major fault, or to the rate of deformation of a region with many faults. The frequency of occurrence of earthquakes with different seismic moments can be estimated from measured values of slip in the region of interest.

It is the purpose of the present work to apply the above formalism to earthquake data from the western Hellenic arc by expressing the frequency of occurrence of earthquakes with different seismic moments in terms of the rate of slip on the subduction zone.

## Recurrence relations for the seismic moment

Beginning from the well known Gutenberg–Richter empirical expression, relating the cumulative frequency of earthquake occurrence $N(m)$ with different magnitude $m$:

$$\log N(m) = a - bm \tag{1}$$

and using another empirical relation between earthquake magnitude $m$ and seismic moment $M_0$:

$$\log M_0 = cm + d \tag{2}$$

where $c$ and $d$ are regression constants which differ from region to region, it can be easily demonstrated (e.g. Molnar, 1979) that the relative number of events $N(M_0)$ with seismic moment greater than or equal to $M_0$ is given by:

$$N(M_0) = qM_0^{-k} \tag{3}$$

where $q = 10^{(a+bd/c)}$ and $k = b/c$.

Molnar (1979) showed that using average rates of slip on faults, this expression can be used to obtain the recurrence interval $T(M_0)$, for events with seismic moments greater than or equal to $M_0$

$$T(M_0) = M_{0,\max}^{1-k} M_0^k / (1-k)\dot{M}_0^s \tag{4}$$

where $M_{0,\max}$ is the maximum possible seismic moment in a region, $\dot{M}_0^s$ is the rate of occurrence of seismic moments $M_0$, and $T(M_0)$ is the average return period for each event with seismic moments greater than or equal to $M_0$.

Equation (4) can be written:

$$\log T(M_0) = \log \frac{M_{0,\max}^{1-k}}{(1-k)\dot{M}_0^s} + k \log M_0 \tag{5}$$

which, because of eqn. (2), becomes:

$$\log T(M_0) = \log \frac{M_{0,\max}^{1-k}}{(1-k)\dot{M}_0^s} r + kbm \tag{6}$$

where $\log r = kd$.

## Empirical seismic moment–magnitude relation from earthquakes in Greece

Obviously, to apply the above formalism to data from the western Hellenic arc, an empirical seismic moment–magnitude relationship is required. Due to the lack of such a relationship for the area of study, we collected all the published seismic moment data for earthquakes in the region and adjacent areas (that is the Greek mainland, the Aegean and Western Turkey) and we present them in Table 1. It should be emphasized, however, that the above data correspond to different seismotectonic units and the derived moment–magnitude relationship is not only based on subduction events. In order to show how the recurrence interval is affected by the use of different moment–magnitude relations we also applied the relationship proposed by Purcaru and Berckhemer (1978).

As it can be seen from Table 1, the bulk of the data come from North (1974, 1977). They have been determined using Rayleigh wave spectral amplitudes. In cases where for the same earthquake the investigator gives moment values deduced from different type of waves (e.g. Prochazkova 1979, 1980), the solution resulting from the surface wave amplitude is tabulated and used in the present regression analysis. When a particular event has been studied in several papers, the latest solution is adopted and included in the data set.

The other parameters of the events listed in Table 1, except that of magnitude, are taken from the bulletins of the International Seismological

TABLE 1

Earthquakes used for magnitude–moment relationships

| No. | Date (y.m.d.) | Time (h:m) | Coord. (°N) | (°E) | $M_s$ | Log $M_0$ | FT * | Reference |
|---|---|---|---|---|---|---|---|---|
| 1 | 1963.02.21 | 17:14 | 32.69 | 20.97 | 5.8 | 24.81 | N | North (1977) |
| 2 | 1963.07.26 | 04:17 | 42.04 | 21.43 | 6.1 | 25.04 | N | North (1977) |
| 3 | 1963.09.18 | 16:58 | 40.71 | 29.02 | 6.3 | 25.43 | N | North (1977) |
| 4 | 1963.12.16 | 13:47 | 36.97 | 20.96 | 5.8 | 24.68 | T | North (1977) |
| 5 | 1964.04.11 | 16:00 | 40.30 | 24.83 | 5.6 | 24.50 | S | North (1977) |
| 6 | 1964.04.29 | 04:21 | 39.25 | 23.72 | 5.5 | 24.34 | T | North (1977) |
| 7 | 1964.07.17 | 02:34 | 38.05 | 23.63 | 6.0 | 25.34 | N | North (1977) |
| 8 | 1964.10.06 | 14:31 | 40.30 | 28.23 | 7.0 | 26.25 | N | North (1977) |
| 9 | 1965.03.09 | 17:57 | 39.40 | 23.82 | 6.3 | 25.23 | S | North (1977) |
| 10 | 1965.03.31 | 09:47 | 38.38 | 22.26 | 6.6 | 26.28 | T | North (1977) |
| 11 | 1965.04.05 | 03:12 | 37.75 | 22.00 | 6.0 | 25.18 | N | North (1977) |
| 12 | 1965.04.09 | 23:57 | 35.06 | 24.31 | 6.1 | 25.39 | S | North (1977) |
| 13 | 1965.04.27 | 14:09 | 35.63 | 23.53 | 5.5 | 25.28 | N | North (1977) |
| 14 | 1965.06.13 | 20:01 | 37.85 | 29.32 | 5.6 | 24.91 | N | North (1977) |
| 15 | 1965.07.06 | 03:18 | 38.37 | 22.40 | 6.4 | 25.62 | N | North (1977) |
| 16 | 1965.11.28 | 05:26 | 36.12 | 27.43 | 5.6 | 24.89 | N | North (1977) |
| 17 | 1965.12.20 | 00:08 | 40.21 | 24.82 | 6.0 | 24.72 | N | North (1977) |
| 18 | 1966.02.05 | 02:01 | 39.10 | 21.74 | 6.2 | 25.36 | N | North (1977) |
| 19 | 1966.05.09 | 00:42 | 34.43 | 26.44 | 5.9 | 25.11 | T | North (1977) |
| 20 | 1966.10.29 | 02:39 | 38.90 | 21.10 | 5.8 | 24.89 | D | North (1977) |
| 21 | 1967.03.04 | 17:58 | 39.60 | 21.29 | 6.8 | 25.96 | N | North (1977) |
| 22 | 1967.05.01 | 07:09 | 39.60 | 21.29 | 6.2 | 25.37 | N | North (1977) |
| 23 | 1967.11.30 | 07:23 | 41.41 | 20.44 | 6.5 | 26.18 | N | North (1977) |
| 24 | 1968.02.19 | 22:45 | 39.40 | 24.94 | 7.2 | 26.82 | S | North (1977) |
| 25 | 1968.05.30 | 17:40 | 35.45 | 27.88 | 5.9 | 25.08 | T | North (1977) |
| 26 | 1968.12.05 | 07:52 | 36.60 | 26.92 | 5.6 | 25.26 | N | North (1977) |
| 27 | 1969.01.14 | 23:12 | 36.11 | 29.19 | 5.9 | 25.72 | T | North (1977) |
| 28 | 1969.03.03 | 00:59 | 40.09 | 27.50 | 5.9 | 24.86 | S | North (1977) |
| 29 | 1969.03.23 | 21:08 | 39.14 | 28.48 | 5.9 | 24.96 | N | North (1977) |
| 30 | 1969.03.25 | 13:21 | 39.25 | 28.44 | 5.8 | 25.26 | N | North (1977) |
| 31 | 1969.03.28 | 01:48 | 38.55 | 28.46 | 6.4 | 26.08 | N | North (1977) |
| 32 | 1969.07.08 | 08:09 | 37.50 | 20.31 | 5.8 | 24.61 | D | North (1977) |
| 33 | 1969.10.13 | 01:02 | 39.78 | 20.59 | 5.7 | 24.53 | D | North (1977) |
| 34 | 1970.03.28 | 21:02 | 36.21 | 29.51 | 7.0 | 26.48 | N | North (1977) |
| 35 | 1970.04.08 | 13:50 | 38.34 | 22.56 | 6.2 | 25.49 | N | North (1977) |
| 36 | 1970.04.16 | 10:42 | 39.02 | 29.91 | 5.7 | 24.64 | N | North (1977) |
| 37 | 1970.04.23 | 09:01 | 39.13 | 28.65 | 5.4 | 24.58 | N | North (1977) |
| 38 | 1970.08.19 | 02:01 | 41.08 | 19.77 | 5.3 | 24.86 | T | North (1977) |
| 39 | 1971.05.12 | 06:25 | 37.64 | 29.72 | 5.8 | 25.60 | T | North (1977) |
| 40 | 1975.01.08 | 19:32 | 38.24 | 22.65 | 5.7 | 24.51 | T | Prochazkova (1980) |
| 41 | 1975.09.12 | 13:10 | 36.27 | 21.90 | 5.0 | 24.40 | – | Prochazkova (1980) |
| 42 | 1975.09.22 | 00:44 | 35.20 | 26.26 | 5.7 | 23.89 | N | Prochazkova (1980) |
| 43 | 1978.05.23 | 23:34 | 40.73 | 23.26 | 5.8 | 24.49 | N | Prochazkova (1980) |
| 44 | 1978.06.20 | 20:03 | 40.82 | 23.15 | 6.4 | 25.76 | N | Barker and Langston (1981) |
| 45 | 1979.04.15 | 06:19 | 42.10 | 19.20 | 7.1 | 26.52 | T | Kim et al. (1984) |
| 46 | 1981.02.24 | 20:53 | 38.20 | 22.90 | 6.7 | 25.86 | N | Jackson et al. (1982) |
| 47 | 1981.02.25 | 02:35 | 38.10 | 23.10 | 6.4 | 25.22 | N | Jackson et al. (1982) |
| 48 | 1981.03.04 | 21:58 | 38.20 | 23.30 | 6.4 | 24.98 | N | Jackson et al. (1982) |
| 49 | 1981.12.27 | 17:39 | 38.90 | 24.90 | 6.5 | 25.51 | S | NEIS |
| 50 | 1981.12.19 | 14:10 | 39.24 | 25.23 | 7.2 | 26.38 | S | NEIS |
| 51 | 1982.01.18 | 19:27 | 39.96 | 24.39 | 6.8 | 25.97 | S | NEIS |

TABLE 1 (continued)

| No. | Date (y.m.d.) | Time (h:m) | Coord. (°N) | (°E) | $M_s$ | Log $M_0$ | FT * | Reference |
|---|---|---|---|---|---|---|---|---|
| 52 | 1982.08.17 | 22:22 | 33.71 | 22.94 | 6.6 | 25.60 | T | NEIS |
| 53 | 1982.11.16 | 23:41 | 40.82 | 19.58 | 5.7 | 24.50 | – | NEIS |
| 54 | 1983.01.17 | 12:41 | 38.03 | 20.23 | 7.0 | 26.38 | T | NEIS |
| 55 | 1983.03.19 | 21:41 | 35.08 | 25.35 | 6.0 | 24.52 | – | NEIS |
| 56 | 1983.03.23 | 23:51 | 38.29 | 20.26 | 6.2 | 25.34 | S | NEIS |
| 57 | 1983.08.06 | 15:43 | 40.14 | 24.77 | 6.7 | 26.08 | S | NEIS |
| 58 | 1984.02.11 | 08:02 | 38.40 | 22.09 | 5.4 | 24.52 | – | NEIS |
| 59 | 1984.05.06 | 09:12 | 38.84 | 25.63 | 5.3 | 24.20 | – | NEIS |

* FT = fault type: N = normal; S-strike-slip; D = dip-slip; T = thrust.

Center ISC and NEIS. The surface wave magnitudes, $M_s$, for the events before 1979 are from Makropoulos and Burton (1981). Since 1979, $M_s$ has been calculated from the ISC body-wave magnitudes by using the conversion formula of Makropoulos and Burton, and so retaining the homogeneity of $M_s$.

The data listed in Table 1 are used to determine the log-linear regression line between seismic moment and surface magnitude. The 59 moment values are plotted in Fig. 1 and the least-squares fit for the log $M_0$, $M_s$ data is:

$$\log M_0 = (1.16 \pm 0.08) M_s + (18.19 \pm 0.5) \quad (7)$$

with a correlation coefficient $r = 0.88$.

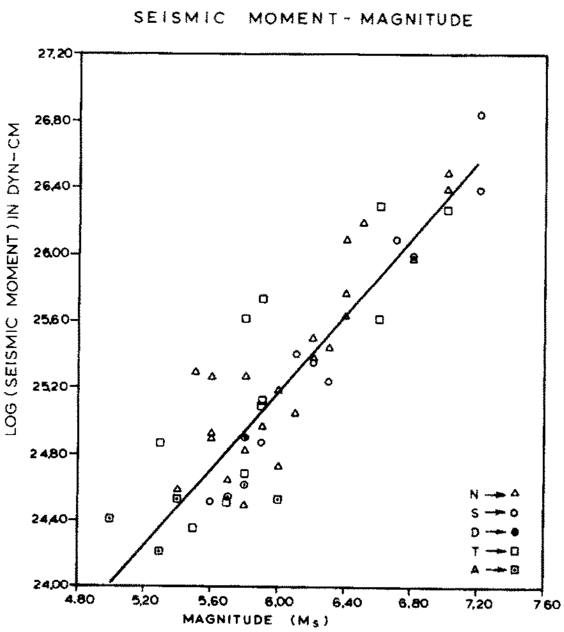


Fig. 1. Seismic moment magnitude relation for 59 earthquakes.

Kiratzi et al. (1985) proposed the following moment–magnitude relationship:

$$\log M_0 = 1.21 M_s + 17.66 \text{ for } 5.5 \leqslant M_s \leqslant 7.4 \quad (7a)$$

based only on 19, mainly shallow, moderate to large earthquakes, which occurred in the Aegean and the surrounding area. The difference in the regression constants $c$ and $d$ results from the different data set used in the analyses.

Difference in $c$ values for the moment–magnitude relations could also be a geographic appearance but not a geographic reality. Hanks and Boore (1984) found such a difference in $c$ values for central and southern California due to small ($M_s < 5$) earthquakes that form the bulk of the central California data set.

In the following, both relationships have been used in order to investigate the dependence of the earthquake recurrence intervals upon the regression constants $c$ and $d$ of the moment–magnitude relationships.

## Regional analysis: cumulative seismic moments and earthquake recurrence intervals

The seismic moments of events with $M_s > 5.2$ which occurred in the area of the western Hellenic arc for the period 1950–1981 inclusive, for which the data set is considered to be complete, were calculated from magnitudes listed in the earthquake catalogue of Makropoulos and Burton (1981), using eqn (7). Listed events down to magnitude 5.2 were considered to dominate the total crustal deformation in the area and give a seismic moment rate of $3.4 \times 10^{25}$ dyn cm yr$^{-1}$.

The 45 earthquakes which were used in the

TABLE 2

Origin time, location, magnitude, depth, seismic moment, cumulative seismic moment, plunge and trend of *A*- /and *C*-axes for the earthquakes used

| No. | Date (y.m.d.) | Time (h:m:s) | Co-ordinates | | Magn. ($M_s$) | Depth (km) | Moment | Cum. moment | *A*-axis | | *C*-axis | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (N) | (E) | | | (dyn cm × $10^{25}$) | | t * | p† | t | p |
| 1 | 1972.09.17 | 14:07:15 | 38.35 | 20.30 | 6.3 | 33 | 3.27 | 3.27 | 122 | 4 | 214 | 20 |
| 2 | 1972.10.30 | 14:32:11 | 38.28 | 20.40 | 5.4 | 13 | 0.30 | 3.57 | 133 | 42 | 36 | 10 |
| 3 | 1953.08.11 | 03:32:27 | 38.35 | 20.70 | 6.8 | 10 | 12.30 | 15.87 | 181 | 1 | 91 | 2 |
| 4 | 1953.08.09 | 07:41:12 | 38.24 | 20.80 | 6.4 | 14 | 4.26 | 20.14 | 349 | 30 | 92 | 21 |
| 5 | 1953.10.21 | 18:39:57 | 38.30 | 20.60 | 6.3 | 13 | 3.27 | 23.41 | 150 | 5 | 60 | 4 |
| 6 | 1953.08.12 | 09:23:55 | 38.10 | 20.70 | 7.2 | 06 | 35.48 | 58.89 | 321 | 5 | 51 | 2 |
| 7 | 1953.08.12 | 13:39:28 | 38.10 | 20.80 | 5.3 | 10 | 0.23 | 59.13 | 171 | 58 | 32 | 66 |
| 8 | 1953.08.12 | 14:08:44 | 38.10 | 20.80 | 6.0 | 10 | 1.47 | 60.60 | 165 | 15 | 77 | 12 |
| 9 | 1953.08.12 | 16:08:38 | 38.05 | 20.80 | 5.3 | 10 | 0.23 | 60.84 | 153 | 66 | 50 | 5 |
| 10 | 1953.08.13 | 03:22:10 | 38.30 | 20.90 | 5.4 | 10 | 0.30 | 61.14 | 319 | 66 | 76 | 12 |
| 11 | 1952.08.12 | 12:05:26 | 37.90 | 20.80 | 6.3 | 10 | 3.27 | 64.41 | 31 | 21 | 289 | 28 |
| 12 | 1976.09.30 | 00:32:58 | 37.40 | 20.30 | 5.3 | 10 | 0.23 | 64.64 | 233 | 5 | 339 | 67 |
| 13 | 1962.07.06 | 09:16:16 | 37.80 | 20.20 | 6.1 | 36 | 1.92 | 66.57 | 147 | 5 | 237 | 5 |
| 14 | 1959.12.01 | 12:38:49 | 37.80 | 20.10 | 5.8 | 15 | 0.87 | 67.44 | 91 | 17 | 358 | 10 |
| 15 | 1962.04.10 | 21:37:10 | 37.70 | 20.10 | 6.3 | 40 | 3.27 | 70.72 | 85 | 12 | 195 | 57 |
| 16 | 1959.11.15 | 17:08:43 | 37.80 | 20.50 | 6.8 | 29 | 12.30 | 83.02 | 51 | 64 | 312 | 64 |
| 17 | 1962.04.11 | 10:47:29 | 37.65 | 20.20 | 5.6 | 20 | 0.51 | 83.53 | 182 | 10 | 278 | 30 |
| 18 | 1975.12.21 | 16:07:51 | 38.47 | 21.70 | 5.5 | 02 | 0.39 | 83.92 | 262 | 44 | 36 | 36 |
| 19 | 1968.03.28 | 07:39:59 | 37.80 | 20.90 | 5.9 | 23 | 1.13 | 85.06 | 54 | 8 | 303 | 72 |
| 20 | 1969.07.08 | 08:09:13 | 37.50 | 20.31 | 5.8 | 33 | 0.87 | 85.93 | 49 | 3 | 176 | 84 |
| 21 | 1958.08.27 | 15:16:35 | 37.40 | 20.70 | 6.4 | 40 | 4.26 | 90.20 | 172 | 2 | 76 | 70 |
| 22 | 1976.05.11 | 17:10:11 | 37.33 | 20.50 | 5.4 | 27 | 0.30 | 90.50 | 349 | 12 | 26 | 84 |
| 23 | 1956.05.15 | 22:56:53 | 37.30 | 20.90 | 5.4 | 10 | 0.30 | 90.80 | 177 | 32 | 80 | 10 |
| 24 | 1958.11.15 | 05:42:40 | 37.50 | 21.70 | 5.4 | 23 | 0.30 | 91.10 | 40 | 25 | 43 | 16 |
| 25 | 1976.06.12 | 00:59:18 | 37.52 | 20.60 | 5.8 | 17 | 0.87 | 91.97 | 23 | 7 | 148 | 83 |
| 26 | 1956.05.16 | 22:56:53 | 37.39 | 20.90 | 5.4 | 10 | 0.30 | 92.28 | 48 | 7 | 230 | 73 |
| 27 | 1957.02.19 | 07:44:00 | 36.25 | 21.70 | 5.9 | 30 | 1.13 | 93.41 | 173 | 20 | 80 | 8 |
| 28 | 1958.05.03 | 20:18:20 | 36.10 | 21.70 | 5.2 | 15 | 0.17 | 93.59 | 270 | 62 | 50 | 26 |
| 29 | 1958.01.02 | 02:08:22 | 36.30 | 22.40 | 5.7 | 22 | 0.66 | 94.26 | 348 | 2 | 78 | 9 |
| 30 | 1962.01.26 | 08:17:40 | 35.30 | 22.80 | 6.2 | 15 | 2.51 | 96.67 | 106 | 24 | 354 | 40 |
| 31 | 1960.03.12 | 11:54:06 | 41.90 | 21.00 | 6.0 | 06 | 1.47 | 98.25 | 92 | 20 | 353 | 27 |
| 32 | 1977.09.11 | 23:19:19 | 34.95 | 23.10 | 6.3 | 04 | 3.27 | 101.52 | 186 | 54 | 76 | 14 |
| 33 | 1972.05.04 | 21:39:57 | 35.15 | 23.60 | 6.5 | 14 | 5.55 | 107.08 | 48 | 8 | 270 | 78 |
| 34 | 1966.11.19 | 07:12:38 | 35.00 | 23.50 | 5.5 | 17 | 0.39 | 107.47 | 265 | 38 | 153 | 30 |
| 35 | 1965.04.27 | 14:09:05 | 35.60 | 23.50 | 5.7 | 37 | 0.66 | 108.14 | 319 | 48 | 124 | 40 |
| 36 | 1959.06.10 | 04:16:02 | 35.60 | 23.60 | 5.5 | 11 | 0.39 | 108.54 | 140 | 40 | 288 | 42 |
| 37 | 1965.04.09 | 23:57:02 | 35.10 | 24.30 | 6.1 | 39 | 1.92 | 110.46 | 190 | 16 | 78 | 44 |
| 38 | 1972.04.29 | 18:29:38 | 34.80 | 24.60 | 5.3 | 48 | 0.23 | 110.69 | 82 | 30 | 197 | 36 |
| 39 | 1969.06.12 | 15:13:31 | 34.40 | 25.00 | 6.1 | 25 | 1.92 | 112.62 | 94 | 46 | 326 | 30 |
| 40 | 1968.10.19 | 15:34:54 | 35.20 | 23.40 | 5.1 | 06 | 0.13 | 112.76 | 52 | 14 | 138 | 38 |
| 41 | 1966.03.11 | 20:01:45 | 34.40 | 24.20 | 5.1 | 30 | 0.13 | 112.89 | 87 | 38 | 206 | 28 |
| 42 | 1969.06.14 | 13:47:26 | 34.40 | 25.00 | 5.2 | 21 | 0.17 | 113.07 | 83 | 60 | 197 | 21 |
| 43 | 1961.08.27 | 22:08:52 | 35.70 | 23.40 | 5.2 | 60 | 0.17 | 113.25 | 105 | 0 | 195 | 55 |
| 44 | 1964.04.08 | 14:12:28 | 35.00 | 24.30 | 5.2 | 64 | 0.17 | 113.43 | 73 | 25 | 260 | 65 |
| 45 | 1968.12.25 | 12:17:19 | 35.00 | 24.30 | 5.2 | 58 | 0.17 | 113.61 | 220 | 57 | 25 | 38 |

* Trend.

† Plunge.

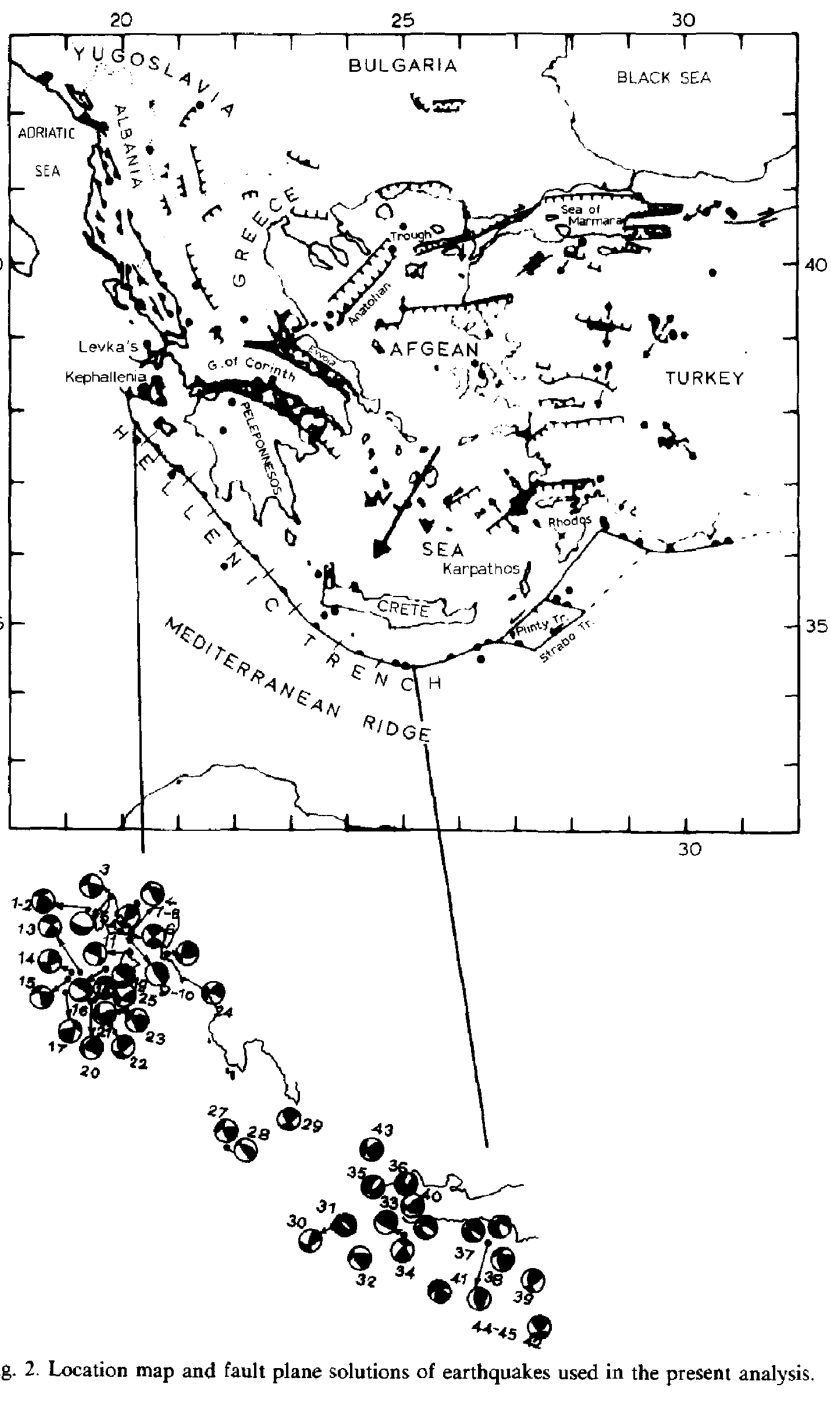


Fig. 2. Location map and fault plane solutions of earthquakes used in the present analysis.

present study are listed in Table 2, and presented in Fig. 2. It is obvious that the stress field along the area investigated is compressional, with the slip vectors dipping towards the arc.

The regional symmetric moment tensor was evaluated for the above earthquakes using the fault plane solutions and the estimated moment values of Table 2. The following formula was used:

$$M_{0,ij} = \sum_{n=1}^{N} M_{0,ij}^{n} \tag{8}$$

where $M_{0,ij}^{n} = M_0(b_i n_j + b_j n_i)$, and $b$ and $n$ are unit vectors in the direction of slip and normal to the fault plane respectively, and $M_0$ is the scalar value of the seismic moment for each magnitude (Aki and Richards, 1980).

For the western Hellenic arc the resultant moment tensor is:

$$\begin{bmatrix} -1.28 & -8.70 & 12.91 \\ -8.70 & -5.99 & 3.95 \\ 12.91 & 3.95 & -11.00 \end{bmatrix} \times 10^{25} \text{ dyn cm}$$

and after diagonalization we obtain:

$$\begin{bmatrix} -23.9 & 0 & 0 \\ 0 & -3.9 & 0 \\ 0 & 0 & 9.5 \end{bmatrix} \times 10^{25}$$

This tensor indicates a maximum compressional component of 23.9 dyn cm along an axis dipping at about 40° and at an azimuth of N37E.

The vertical distribution of the seismic moments in the region is shown in Fig. 3, indicating that the released seismic moment is reduced drastically below the depth of 40 km, verifying the shallow seismic activity of the area.

Historical data (Papazachos and Comninakis, 1982) indicate that during the 19th century at least seven shocks or intermediate shocks with magnitudes ranging from 7 up to 8.3 occurred in the Hellenic arc. Setting the maximum expected magnitude for a series of earthquakes in the region to be 7.8, 7.9 and 8.0, this corresponds to maximum seismic moment values of 1.72, 2.25 and 2.95 ($\times 10^{27}$) dyn cm respectively.

Considering a value of 2/3 for $k$ (Kanamori and Anderson, 1975) and a seismic moment rate

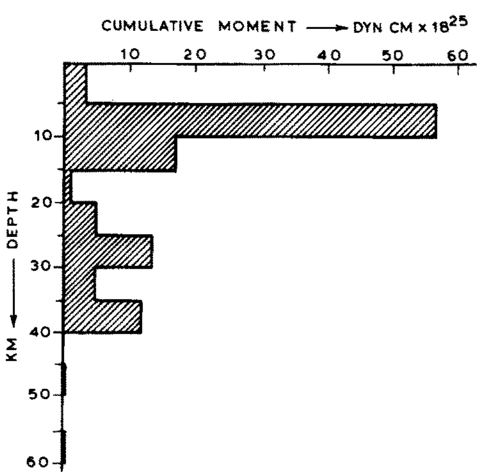


Fig. 3. Cumulative seismic moment vs. depth for the area investigated.

(see Table 2) of $3.4 \times 10^{25}$ dyn cm yr$^{-1}$, eqn (6) is used to plot the earthquake recurrence intervals versus magnitude (Figs. 4a and b). For example, according to Fig. 4a, considering a maximum expected magnitude of 8.0, earthquakes of magnitude 7, 7.5 and 8 will have return periods of about 45, 90 and 262 years, respectively.

Next, we attempt an estimation of the subduction rate in order to apply it to the seismic hazard of the Antikithira gap (Lyberis et al., 1982). Using the data of Table 2, an estimated arc length of about 100 km (Wyss and Baer, 1981) and applying Brune's formula (Brune, 1968)

$$\bar{u} = \Sigma(M_0/\mu)LW$$

a subduction rate of 1.13 cm/yr was calculated, assuming a slab thickness of 20 km (see Fig. 3) and a value of the modulus of rigitidy $\mu = 3 \times 10^{11}$ dyn cm$^{-2}$. The above relationship does not introduce any limitation to the analysis of displacements occurring along major transform faults and in zones of shallow underthrusting beneath island arcs (Brune, 1968; Davies and Brune, 1971).

The subduction rate obtained in this study is less than that predicted by what seems to be a quite plausible model for the tectonics of this region, and far lower than those estimated by applying the same technique in other arc–trench systems of the world (McGarr, 1977). The accuracy of the above result may be affected by the small time interval considered, and perhaps the level of seismicity at the area during the investigated period is not representative of a longer time average. In fact, 73% of the cumulative seismic moment was released (Table 2) between 1953 and 1960, and 47% of the total seismic moment was released by the 1953 Cephallonia earthquake sequence.

Errors in calculating seismic moments from magnitudes by using eqn. (7) are due primarily to uncertainties in estimating magnitudes. Earthquake magnitudes are commonly determined to within 1/4 of a unit, which corresponds to a possible error in the calculation of the magnitude of $10^{1.08/4} = 1.86\%$. On the other hand, the effect of a small earthquake was estimated to have a contribution of less than 4% (Tselentis and Makropoulos, 1986).

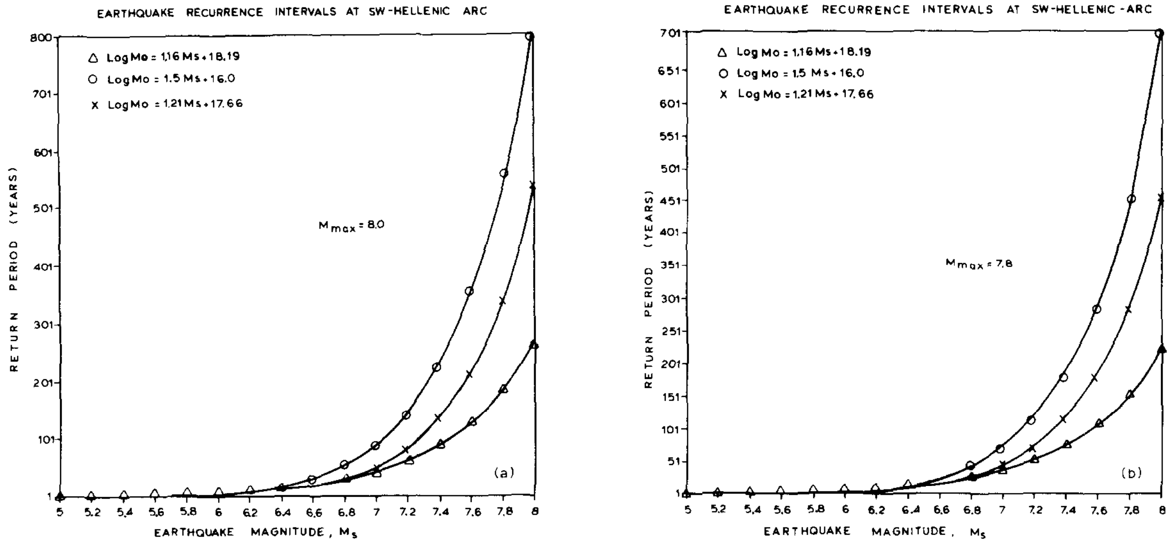


Fig. 4. Earthquake recurrence intervals at the southwest Hellenic arc (a) for different maximum expected magnitudes, and (b) for different moment–magnitude relationships.

Regardless of the error in the calculated slip rate, the subduction of the Mediterranean lithosphere under the Aegean lithosphere requires a considerable amount of aseismic slip, a result that is perhaps not surprising but is different from that of most arc–trench systems. Similar results were found from investigations in nearby regions of the Mediterranean and Middle East by North (1974), who suggested that a major proportion of the deformation takes place in viscoelastic processes such as creep.

By application of Brune's model and for four different subduction rates, the seismic moment rates at the Antikithira gap are estimated, by using the above-mentioned dimensions of the gap. The results are listed in Table 3. The estimated earthquake recurrence intervals are shown in Fig. 5.

TABLE 3

Moment rates corresponding to the subduction rates used in the present analysis

| Subduction rate (cm/yr) | Moment rate (dyn cm $yr^{-1} \times 10^{24}$) |
|---|---|
| 1.13 | 6.78 |
| 1.50 | 9.00 |
| 2.0 | 12 |
| 2.5 | 15 |

In order to investigate how the parameters $c$ and $d$ of the moment–magnitude relation affect the earthquake recurrence interval, the relationship (7a) proposed by Kiratzi et al. (1985) has been incorporated in the present model to estimate the maximum expected seismic moment $M_0^{max}$ which corresponds to two different values ($M_s = 7.8$ and $M_s = 8.0$) of the maximum ex-

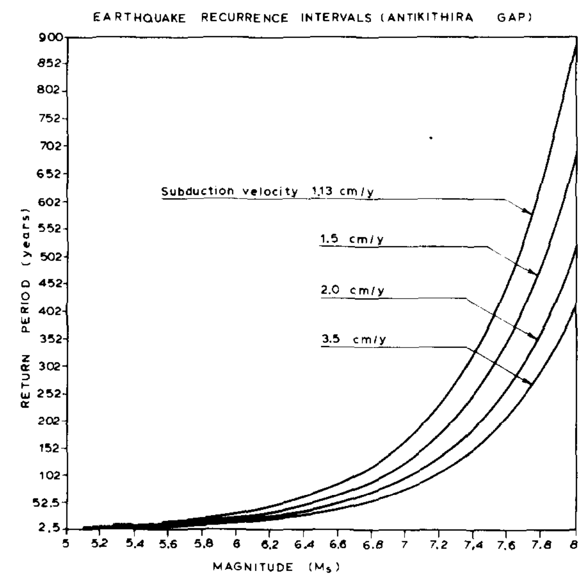


Fig. 5. Earthquake recurrence intervals at Antikithira gap for different subduction rates.

pected earthquake magnitude in the area investigated.

For the same purpose, the relationship $\log M_0 = 1.5 M_s + (16.1 \pm 0.1)$ $(5 \leqslant M_s \leqslant 7.5)$ proposed by Purcaru and Berckhemer (1978) has been applied. The estimated earthquake recurrence intervals are shown in Fig. 4 in comparison with that obtained by the moment–magnitude relationship derived in this study.

The striking difference between the two relationships, which are based only on Greek earthquakes, is in the return period for seismic events with magnitude greater or equal to 7.0. This is probably due to the different data which have been used in the deriviation of each relationship. Similarly, the estimated return periods for earthquakes with $M_s \geqslant 6.8$ based on the Purcaru and Berckhemer's relationship are longer than that obtained by the corresponding formula derived in this study. In particular, for very large events with $M_s \geqslant 7.2$, the recurrence intervals differ by a factor of 2 or 3.

It seems reasonable to consider that the recurrence intervals for earthquakes which occurred along the southwestern part of the Hellenic arc, and are based on the moment–magnitude relationship derived in this study, are most realistic in comparison with those obtained by using other relevant relationships.

Wyss and Baer (1981), in work based on seismicity studies along the Hellenic arc, suggest that a large earthquake of $M_s = 7.75 \pm 0.5$ should be expected between 1980 and 1990, either in the southwestern part of the Hellenic arc, which was ruptured in a series of large to great earthquakes, mostly during the 19th century, with the last earthquake occurring in 1903. We may assume that the return period of events with $M_s = 7.75 \pm 0.5$ varies between 80 and 150 yrs, which is consistent with the computed recurrence intervals in this study.

## Discussion and conclusions

The present work attempts to express the frequency of occurrence of major earthquakes at the southwestern Hellenic arc in terms of the seismic moment rate released in the area.

For this purpose, the Gutenberg–Richter empirical formula relating frequency of occurrence as a function of magnitude is combined with a derived empirical relation between earthquake magnitude and seismic moment. The frequency of occurrence is expressed either in terms of the seismic moment of actual events (Fig. 4) or in terms of various subduction rates at the Hellenic arc (Fig. 5).

It should be emphasized, however, that the number of earthquakes which have occurred along the Hellenic arc with reliable seismic moments is too small to allow us to establish a relevant moment–magnitude relationship based only on subduction events. For this reason we extended the data by including events occurring in the Aegean and Surrounding area.

A critical point in evaluating earthquake recurrence intervals based on the present model is the moment release rate along the subduction zone. Peterson and Seno (1984) studied the factors affecting the seismic moment release rates in subduction zones and found out that the moment rate release decreases as the subduction rate increases or as the age of the subducting lithosphere increases. This fact is verified by assuming different subduction velocities in the estimation of the earthquake recurrence interval at Antikithira gap. Figure 5 shows that a variation of the subduction velocity by a factor of three results in a corresponding change by a factor of about three in earthquake recurrence intervals.

It should be mentioned, that, in this study, the seismic slip rate is obtained by using Brune's model, which is appropriate along major plate boundaries. In regions such as intraplate Japan (Wesnousky et al., 1982), where seismic energy release is not concentrated along one fault but rather is divided among a large network of faults, it is more suitable to estimate the slip rate resulting from the movements on all faults by applying other models (Kostrov, 1974; Chen and Molnar, 1977).

Finally, in order to investigate the dependence of the return period upon the parameters $c$ and $d$ of the moment–magnitude relationship, we incorporated in the present model different $M_0$–$M_s$ relationships based on different earthquake data. The results showed that the recurrence intervals are strongly dependent on the $M_0$–$M_s$ relationship, especially for large earthquakes ($M_s \geqslant 7.0$), and more attention should be given to the selection of the relevant moment–magnitude relation.

Based on the $M_0$–$M_s$ relationship derived in this study, a return period of 80 to 100 years is obtained, for earthquakes of magnitude class 7 which have occurred along the southwestern part of the Hellenic arc.

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