TIME VARIATION OF SEISMICITY AND SEISMIC HAZARD IN THE HELLENIC ARC-TRENCH SYSTEM

G.F. Karakaisis, C.B. Papazachos, E.M. Scordilis, Ch.A. Papaioannou and B.C. Papazachos
Department of Geophysics, School of Geology, Aristotle University, Thessaloniki 54124, Greece
Corresponding author: George Karakaisis, e-mail karakais@geo.auth.gr, tel.: +30310 998484, fax: +30310 998528.

ABSTRACT

Investigation of the time variation of large shocks (M≥6.6) which occurred during the last two centuries in the Hellenic arc-trench system (34.0°N-37.2°N, 21.0°E-30.0°E) shows that quite periods with durations of about five decades are preceded and followed by active periods with durations of about three decades and that no such large shock has occurred in this system during the last 45 years (1957-2001). The time variation of seismic hazard in the sedimentary part of the Hellenic arc (expressed by the macroseismic intensity I_o≥VIII) shows similar behavior. Based on this pattern of the time variation of seismicity and seismic hazard we may conclude that seismic quiescence in the Hellenic arc-trench system approaches its end and an active period will probably start during the next decade, in agreement with independent results from accelerated seismic deformation studies.
Key words: Southern Aegean, seismic hazard, seismicity, Hellenic arc

INTRODUCTION

Southern Aegean (34°N-37.2°N, 21°E-30°E) includes most of the sedimentary part of the Hellenic arc where convergence of the Aegean lithosphere (front part of Eurasian lithospheric plate) and the eastern Mediterranean lithosphere (front part of the African lithospheric plate) takes place in an about north-south direction. The rate of this convergence is considerable with respect to stable Europe (~4cm/yr), and is mainly due to the overriding of the Aegean lithosphere on the Mediterranean lithosphere (~3cm/yr). It is also partly due to the northward motion of the African lithospheric plate (1cm/yr) with respect to the Eurasian lithospheric plate and subduction of the eastern Mediterranean lithosphere under the southern Aegean lithosphere (Papazachos 1999). For this reason shallow (h≤40km), as well as intermediate depth (h=41km-100km) earthquakes occur in southern Aegean with magnitudes up to about 8.0 (Papazachos, 1990).

Attempts to investigate the time variation of seismicity in the Hellenic arc have been made by several seismologists during the last two decades (Ambraseys, 1981; Wyss and Baer, 1981; Papazachos and Comninakis 1982; Papazachos *et al*., 1985; Papadimitriou *et al*., 1985, 1988; Papadopoulos, 1986, 1988). A result of this work, which is directly related to the present paper, is the observation that southern Aegean forms a seismic gap for strong earthquakes since 1957 (Papadimitriou *et al*., 1985, 1988; Papazachos *et al*., 1985). This area (34°N-37.2°N, 21°E-30°E) is still a seismic gap because no large (M≥6.6) shallow or intermediate depth mainshock occurred there since 1957. This is one of the two reasons, which motivated the present study. The second reason is a recent research work (Papazachos *et al.*, 2002) that led to the identification of two elliptical regions, one in the southwestern part of the Hellenic arc and the other in its eastern part, which are currently in an accelerating seismic excitation that may lead to the generation of large mainshocks.

In the present paper the time variation of the rate of occurrence of the large (M≥6.6) or/and destructive (I≥VIII) earthquakes in the southern Aegean region (34°N-37.2°N, 21°E-30°E) is examined in order to estimate the expected strong earthquake seismic activity and seismic hazard during the next decade in this region.

THE DATA

The data used in the present paper are from the catalogue of Papazachos *et al.* (2001). The magnitudes of the earthquakes in this catalogue are given in an equivalent moment magnitude scale. The main part of these data are given in table (1), where we present the epicentral coordinates, the focal depth (h=n for h≤40km, h=i for h>40-100km), the moment magnitude, the location and the value of the maximum observed intensity (in the MM scale) for

Table 1. *Information on all mainshocks with M≥6.6 or/and on all mainshocks with maximum intensity I_o≥VIII which occurred in the southern Aegean area since 1842. For each mainshock there are listed the date of occurrence (year, month, day), the epicenter coordinates (north latitude, east longitude), the focal depth h (in km) which is denoted by n or i for h≤40km and h=41-100km respectively, the moment magnitude, M, and the site where the maximum intensity I_o has been observed.*

No	Date	φ_N^0, λ_E^0	h	M	Site (I_o)
1	1842.04.18	36.7 22.3	n	6.7	Mane (VIII)
2	1843.10.18	36.4 27.7	n	6.6	Chalke (IX)
3	1846.03.28	35.8 25.0	i	7.3	Heraklio (VII)
4	1846.06.10	37.1 22.0	n	6.6	Messini (X)
5	1851.02.28	36.6 28.8	n	6.8	Leivesia (X)
6	1856.10.12	35.6 25.8	i	7.7	Heraklio (IX)
7	1863.04.22	36.4 27.6	i	7.5	Rhodos (X)
8	1866.02.06	36.1 22.9	n	6.6	Cythera (VIII)
9	1867.09.20	36.7 22.6	n	6.8	Maroulia (IX)
10	1869.04.18	36.5 27.6	n	6.8	Syme (IX)
11	1869.12.01	37.0 28.3	n	6.8	Marmaris (IX)
12	1870.02.22	36.5 28.8	n	6.6	Makre (VII)
13	1885.03.28	37.1 22.0	n	6.0	Messini (VIII)
14	1886.08.27	37.0 21.4	n	7.3	Philiatra (X)
15	1887.07.17	35.7 25.8	i	7.2	Heraklio (VII)
16	1899.01.22	37.2 21.6	n	6.5	Kyparissia (IX)
17	1903.08.11	36.4 23.0	i	7.2	Cythera (IX)
18	1908.05.17	35.7 25.2	i	6.7	Heraklio (V)
19	1910.02.18	35.7 23.8	i	6.8	Chania (VIII)
20	1922.08.13	35.0 26.8	n	6.8	Zakros (VII)
21	1923.08.01	35.0 25.0	i	6.6	Rethymno (IV)
22	1926.03.18	36.1 29.6	n	6.9	Kastelorizo (VIII)
23	1926.06.26	36.5 27.5	i	7.6	Archagelos (XI)
24	1926.08.30	36.5 23.3	i	7.2	Sparte (VIII)
25	1927.07.01	36.8 22.3	n	7.1	Oetylo (IX)
26	1933.04.23	36.8 27.3	n	6.6	Cos (IX)
27	1935.02.25	35.9 25.2	i	7.0	Anogheia (VIII)
28	1941.05.23	37.0 28.1	n	6.0	Mugla (VIII)
29	1942.06.21	36.0 27.0	i	6.3	Makre (VIII)
30	1944.07.30	36.6 22.3	n	6.0	Kambos (VIII)
31	1947.10.06	37.0 21.7	n	7.0	Pylia (IX)
32	1948.02.09	35.7 27.0	n	7.1	Karpathos (IX)
33	1948.07.24	35.2 24.4	i	6.6	Chania (V)
34	1952.12.17	34.4 24.5	n	7.0	Heraklio (VI)
35	1956.07.09	36.6 26.0	n	7.5	Amorgos (IX)
36	1957.04.25	36.5 28.6	n	7.2	Rhodos (VIII)
37	1959.04.25	36.9 28.7	n	6.2	Koycegiz (VIII)
38	1959.05.14	35.0 24.7	n	6.3	Pitsidia (VIII)
39	1986.09.13	37.1 22.1	n	6.0	Kalamata (IX)

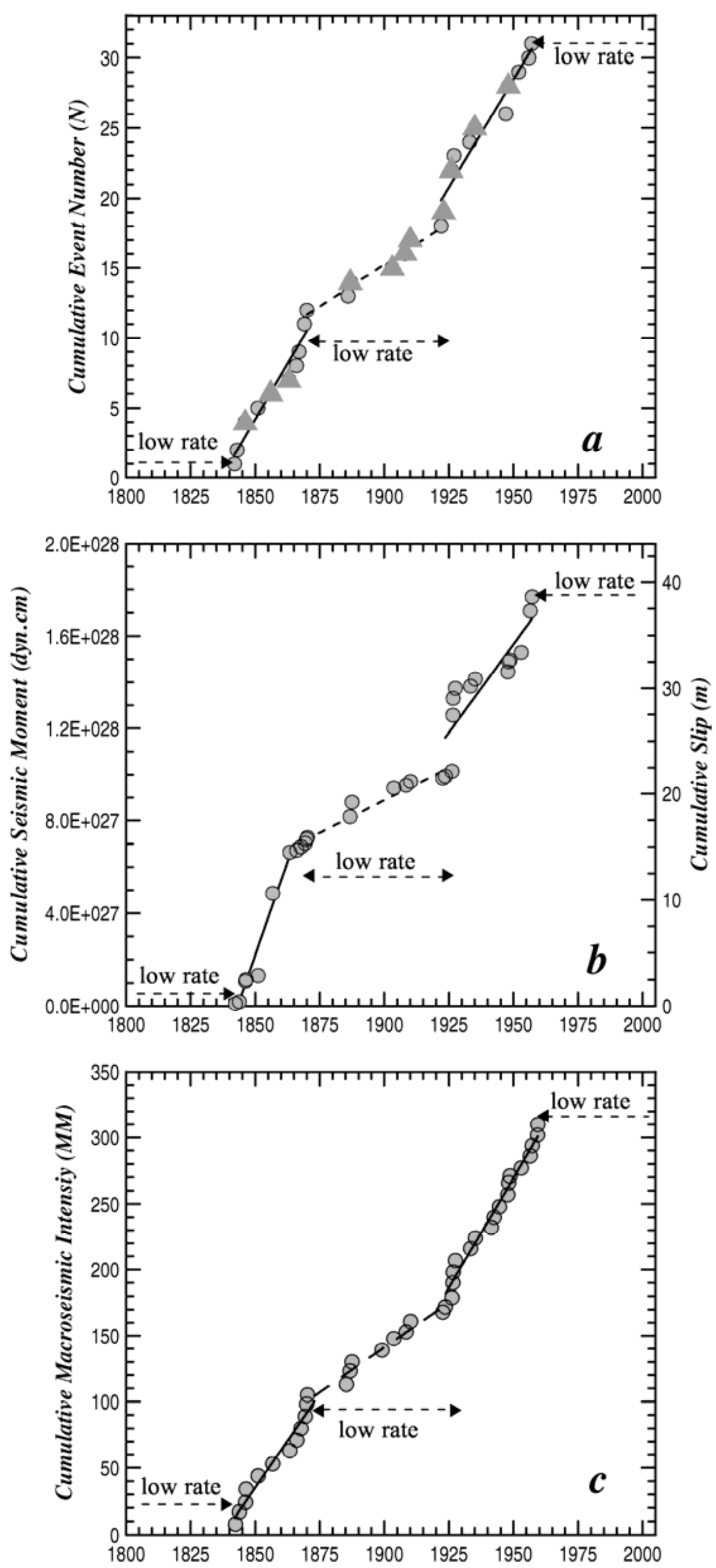

Figure 1. *(a) The cumulative number, N, of large (M≥6.6) mainshocks in southern Aegean as a function of time. Circles and triangles denote shallow (h≤40km) and intermediate focal depth (40<h≤100km) mainshocks, respectively. (b) The cumulative seismic moment (left axis) and the cumulative slip (in m, right axis) of the same earthquakes as a function of time. (c) The cumulative number of the macroseismic intensities I_o≥VIII of the earthquakes listed in table (1) as a function of time. In all plots a quiescence period can be observed after 1957.*

all mainshocks which occurred in southern Aegean since 1842 and have M≥6.6 or/and maximum intensity I_o≥VIII. This data sample (1842-2001, M≥6.6) was selected because it is complete for the examined time period (Papazachos *et al.*, 2001). Only information of mainshocks are used in this study, that is, no information for foreshocks or aftershocks were considered since such information is not important for long term variation of seismicity and seismic hazard. Moreover, during the historical (pre- instrumental) period the parameters of even the strong foreshocks and aftershocks are not well known.

TIME VARIATION OF THE FREQUENCY OF LARGE EARTHQUAKES IN SOUTHERN AEGEAN

Figure (1a) shows the time variation of the cumulative number, N, of large (M≥6.6) mainshocks in southern Aegean. Circles show shallow mainshocks (h≤40km) and triangles show intermediate focal depth (40<h≤100km) mainshocks. It is clear that the rate of generation of these mainshocks varies during the examined period (1842-2001). Four time intervals can be observed with respect to this rate. During the first (1842-1870) and the third (1923-1957) intervals this rate is high (r_1=0.44 and r_3=0.41 events/year). We know that the first active period started in 1842 because before that period, for 26 years no destructive earthquake occurred in the Hellenic arc (Papazachos and Papazachou 1997). During the second interval (1870-1923) the rate is much lower (r_2=0.11 events/year), while during the fourth (last) time interval no such earthquake occurred (r_4=0.0 events/year since 1957). The same pattern of alternating periods of low and high seismic activity can be observed in Figure (1b) where the cumulative seismic moment and the cumulative slip of these (M≥6.6) mainshocks have been plotted as a function of time. These measures of the earthquake size have been derived through relations, which apply for earthquakes in the broader Aegean area (Papazachos and Papazachou, 1997).

As can be concluded from table (1) and figure (1), the duration of these two active time intervals in southern Aegean is about three decades (t_1=27.8 yrs, t_3=34.7yrs). The two largest mainshocks (M>7.5) of the whole examined period occurred in these two active intervals. The mean return period of the mainshocks with M≥6.6 during both active intervals is about 2 years.

The duration of the single time interval (1870-1923) with low seismicity rate is about five decades (t_2=52.5 yrs) and the mean earthquake return period during this interval is about 10 years. The largest earthquake during this period of low seismicity rate had a magnitude equal to 7.3. On the other hand, the duration of the currently observed seismic quiescence period in southern Aegean is also approaching the five decades (t_4=44.7yrs) and no earthquake with M≥6.6 has occurred in this area during this time interval. It is therefore reasonable to make the hypothesis that this period of quiescence for the large earthquakes may end during the next decade and a period of high activity will start which will last about three decades.

To further demonstrate the currently observed seismic quiescence for large earthquakes in the area of southern Aegean we have used only instrumental data, which are more reliable than the historical ones. Figure (2) is a map of the Aegean area where the epicenters of all mainshocks that occurred between 1911 (when the first reliable seismograph was installed in Athens) and 2001 with magnitudes M≥6.0 and focal depths h≤100km are shown. Circles indicate shallow shocks (h≤40km) and triangles correspond to intermediate focal depth shocks (40km<h≤100km). The upper part of the figure shows data for the period 1911-1957 and the lower part data for the period 1957-2001. It is obvious that large magnitude seismicity has been severely reduced during the present quiescence period.

TIME VARIATION OF SEISMIC HAZARD IN SOUTHERN AEGEAN

Knowledge of seismic hazard is even more important than the basic parameters of earthquakes (seismic focus, magnitude) from practical point of view. Maximum macroseismic intensity, I_o (in the MM scale), was adopted in the present study as a measure of seismic hazard. The values of I_o have been estimated from the macroseismic effects of the earthquakes (damage in buildings, number of deaths, etc.) and can be considered as quite reliable. Plot of the values of I_o≥VIII as a function of time (Fig. 1c) gives a pattern similar to figures (1a, b), with

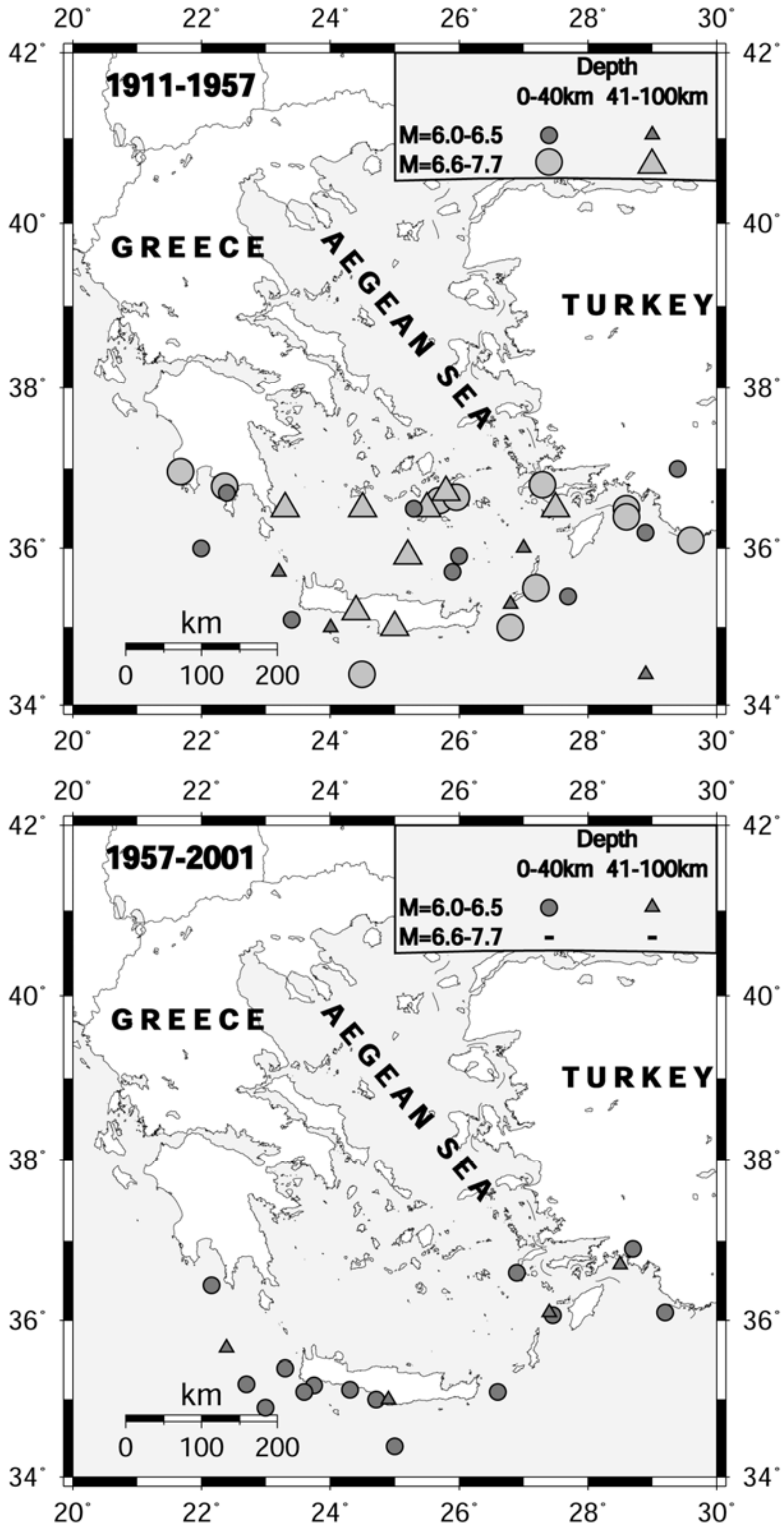

Figure 2. *Epicenters of all strong ($M \geq 6.0$) earthquakes with focal depth $h \leq 100km$, that occurred in the southern Aegean area during 1911-1957 (top) and 1957-2001 (bottom). No large ($M \geq 6.6$) mainshock has occurred in this area since 1957.*

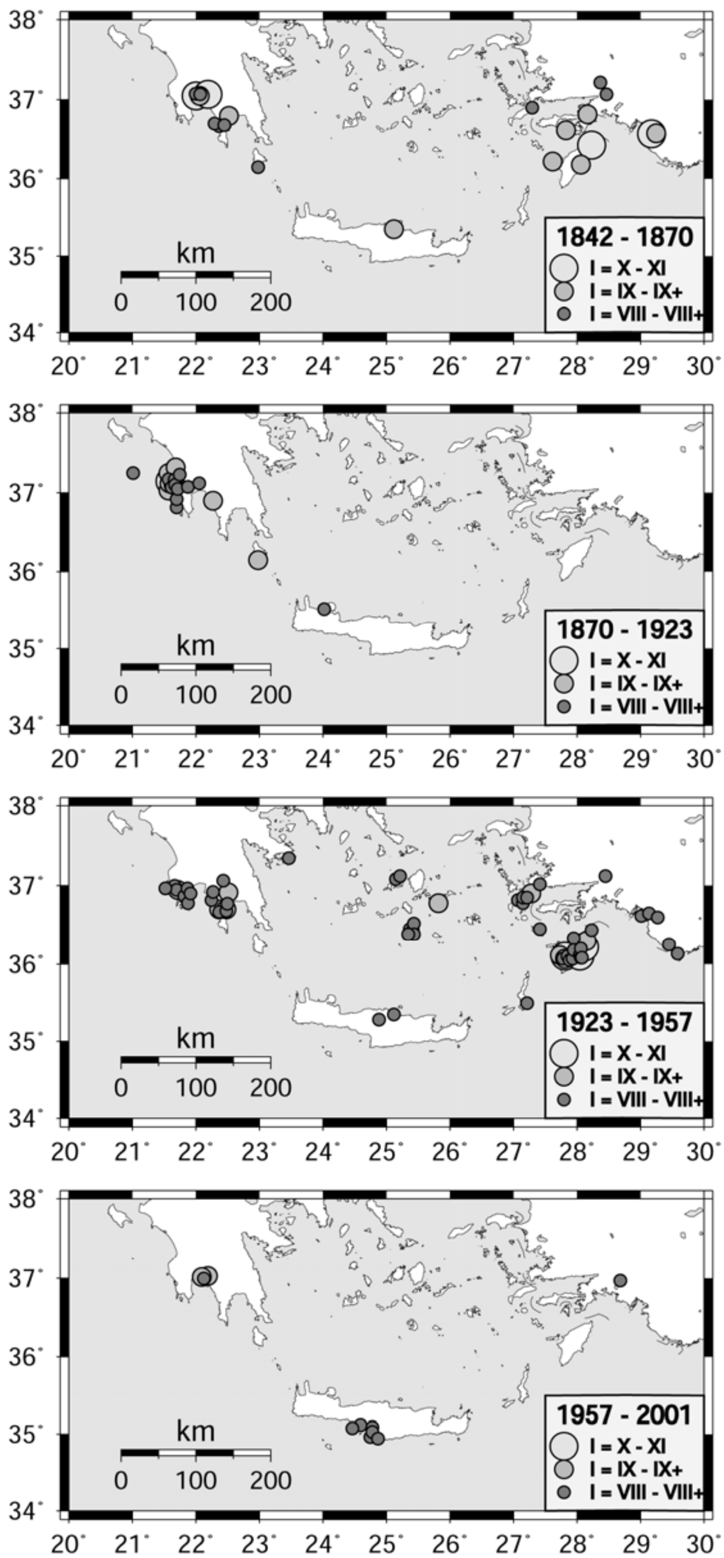

Figure 3. The sites where damage due to strong earthquakes in the southern Aegean area has been observed (macroseismic intensities I≥VIII) during the four consecutive time intervals 1842-1870, 1870-1923, 1923-1957 and 1957-2001. During the last time interval only three places suffered damage of intensity I =VIII-IX.

some deviations due to the fact that even earthquakes with M<6.6 cause damage of intensity I≥VIII.

Figure (3) shows a map of the southern Aegean area where the places with macroseismic intensities I=VIII, I=IX and I=X are denoted by circles of three corresponding sizes. In the four parts of this figure the geographical distribution of intensities is shown for the periods 1842-1870, 1870-1923, 1923-1957 and 1957-2001, respectively. It is observed that during the two periods of high seismic activity (t_1, t_3) high macroseismic intensities are distributed all over the Hellenic arc, from its southwestern part up to its eastern part (south Peloponnese–Cythera–Crete–Dodecanese). During the period of low seismic activity (t_2=1870-1923) only several places at the western part of the Hellenic arc have suffered damage of intensity VIII-IX degrees, while during the last time period (t_4), even fewer observations of VIII-IX intensity values have been reported. We can, therefore, reasonably assume that during the oncoming period of expected high seismicity the whole area of southern Aegean (Hellenic arc) will suffer significant damage.

CONCLUSIONS

The time variation of the large (M≥6.6) shallow and intermediate depth mainshocks in the Hellenic arc-trench system has not been constant during the last two centuries. It seems that periods of quiescence with duration of the order of five decades are preceded and followed by very active periods with duration of about three decades. During these active periods the frequency of shocks is one mainshock per two years and high macroseismic intensities are observed all along the sedimentary part of the arc. Taking into account these observations and the fact that no large (M≥6.6) mainshock occurred in any part of this system since 1957 we may reasonably conclude that this quiescence approaches its end and a period of high, large earthquake seismic activity will start during the next decade.

Recent observations have shown that the intermediate magnitude seismic activity is now at an accelerating state in the southwestern and the eastern part of the Hellenic arc and that this activity may lead to the generation of large mainshocks there during the next few years (Papazachos *et al.* 2002). This further supports the hypothesis that strong seismic activity must be expected in the Hellenic arc-trench system within the next years that may cause significant damage to the nearby urban areas.

ACKNOWLEDGMENTS

The GMT software (Wessell and Smith, 1995) was used to generate the maps of this study. This work has been partially supported by the Greek Planning and Protection Organization (OASP), (Res. Comm. AUTH project 20242) and is a Geophysical Laboratory contribution number #0556/2001.

REFERENCES

Ambraseys, N.N., 1981. On the long term seismicity of the Hellenic arc, *Boll. Geofis. Teor. Appl*., 23, 355-359.

Papadimitriou, E.E., Karacostas, B.G., Karakaisis, G.F. and Papazachos, B.C., 1985. Space-time patterns of seismicity in the Aegean and surrounding area, *Proc. 3rd Intern. Symp. Analys. Seismicity and Seismic Risk, Liblice, Czecholslovakia, 17-22 June 1985*, 40-44.

Papadimitriou, E.E., Karacostas, B.G., Karakaisis, G.F., and Papazachos, B.C., 1988. A seismicity premonitory pattern in southern Aegean area, *Proc. 16th Gen. Assembl. Europ. Seismol. Com*., *Moscow, October 1-6, 1984*, *Nauka*, 66-70.

Papadopoulos, G.A., 1986. Long–term earthquake prediction in the Western Hellenic Arc, *Earthq. Predict. Res*., 4, 131-137.

Papadopoulos, G.A., 1988. Synchronized earthquake occurrence in the Hellenic Arc and implications for earthquake prediction in the Dodecanese islands (Greece), *Tectonophysics*, 145, 343-347.

Papazachos, B. C., 1990. Seismicity of the Aegean and surrounding area, *Tectonophysics*, 178, 287-308.

Papazachos, B.C. and Comninakis, P.E., 1982. Long-term earthquake prediction in the Hellenic trench–arc system, *Tectonophysics*, 86, 3-16.

Papazachos, B.C., Papadimitriou, E.E., Karacostas, B.G., and Karakaisis, G.F., 1985. Long term prediction of great intermediate depth earthquakes in Greece, *Proc. 12th Regional Sem. Earthq. Engin., EAEE, EPPO, September 1985, Halkidiki- Greece*, 1-12.

Papazachos, B.C. and Papazachou, C.B., 1997. *The earthquakes of Greece*, Editions Ziti, Thessaloniki, p. 304.

Papazachos, B.C., Comninakis, P.E., Karakaisis, G.F., Karacostas, B.G., Papaioannou, Ch.B., and Scordilis, E.M., 2001. A catalogue of earthquakes in Greece and surrounding area for the period 550BC-1999, *Publication of the Geophysical Laboratory, University of Thessaloniki* (also at *http://geohazards.cr.usgs.gov/iaspei/europe/greece/the/catalog.txt*).

Papazachos, C. B., 1999. An alternative method for a reliable estimation of seismicity with an application in Greece and surrounding area, *Bull. Seism. Soc. Am*., 89, 111-119.

Papazachos, C.B., Karakaisis, G.F., Savvaidis, A.S. and Papazachos, B.C., 2002. Accelerating seismic crustal deformation in the southern Aegean area, *Bull Seism. Soc. Am*., (in press).

Wessel, P., and Smith, W., 1995. New version of the Generic Mapping Tools, *EOS Trans. A. G. U.*, 76**,** 329.

Wyss, M. and Baer, M., 1981. Earthquake hazard in the Hellenic arc, In: D. W. Simpson and P. G. Richards (eds), *Earthquake Prediction, an International Review*, A. G. U., Washington D. C., pp. 153-172.