ON INTERMEDIATE TERM EARTHQUAKE PREDICTION IN GREECE BASED ON THE ALGORITHM M8

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A B S T R A C T

In the present study an attempt is made to identify the Times of Increased Probability (TIPs) of occurrence of a moderate earthquake ($M_L \geq 5.5$) by premonitory intermediate-term seismic activation in lower-magnitude range, as defined in the algorithm M8. A previous study has shown that 10 out of 11 earthquakes with $M_L \geq 5.5$ which took place in Greece in the time period 1977-1990, occurred within TIPs diagnosed retrospectively indicating that the algorithm M8 can also be applied for smaller earthquake in regions for which complete catalogues are available.

By scanning the territory of Greece and adjacent areas four regions are diagnosed as candidate for earthquake of $M_L \geq 5.5$ since they have already entered in TIPs. The results obtained here by no means constitute a definitive earthquake prediction but simply outline the territories which deserve for more detailed and comprehensive analysis. Monitoring of their seismicity would provide further insight to the ongoing research on localization of the impending earthquakes within TIPs.

ΕΝΔΙΑΜΕΣΟΥ ΧΡΟΝΟΥ ΠΡΟΓΝΩΣΗ ΣΕΙΣΜΩΝ ΣΤΗΝ ΕΛΛΑΔΑ ΜΕ ΕΦΑΡΜΟΓΗ ΤΟΥ ΑΛΓΟΡΙΘΜΟΥ Μ8.

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Π Ε Ρ Ι Λ Η Ψ Η

Στην παρούσα εργασία εφαρμόστηκε ο αλγόριθμος Μ8 για την ενδιαμέσου χρόνου πρόγνωση σεισμών στον Ελληνικό χώρο με τοπικό μέγεθος $M_L \geq 5.5$. Σε προηγούμενη μελέτη δείχτηκε ότι ο αλγόριθμος Μ8 έχει εφαρμογή στον Ελληνικό χώρο, προβλέποντας "εκ των υστέρων" 10 από 11 σεισμούς της περιόδου 1977-1990. Διερευνώντας τον χώρο αυτό διαπιστώθηκε ότι 4 περιοχές έχουν ήδη εισέλθει σε TIP, και παρουσιάζονται αναλυτικα τα αποτελέσματα.

INTRODUCTION

Several studies of precursors to past events suggest that seismicity patterns can play an important role in earthquake prediction programs in the future. A number of authors have examined seismicity prior to past earthquakes and proposed various patterns as precursors. The first comprehensive review of those studies was made by Kanamori (1981) and McNally (1982) who outlined the basic types of seismicity precursors, such as, foreshocks, quiescence, swarms, accelerated activity, and doughnuts. Although seismic quiescence has received the most attention from the seismicity patterns (see review in Habermann, 1988; Wyss and Habermann, 1988), many reported observations of quiescence seem to have problems either due to the statistical inadequacies in the treatment of the data (Reasenberg and Matthews, 1988) or due to magnitude bias in earthquake catalogues (Habermann, 1982).

On the other hand, pattern recognition techniques have been developed (Celfand et al., 1976; Gabrielov et al., 1986) in order to examine whether the time interval (t, t+τ) belongs to a Time of Increased Probability (TIP) of a strong earthquake (τ is considered as a numerical parameter). For this purpose, two algorithms for diagnosis of TIPs have been proposed and applied to different seismic regions of the world. The first one, the so called CN-algorithm was designed for the analysis of the earthquake catalogues for California and Nevada. In this case, strong earthquakes were defined by the threshold M_0 = 6.4 (Allen et al., 1987). The second one, the algorithm M8, based on the concept of self-similarity of earthquakes was designed by Keilis-Borok and Kossovokov (1984, 1986) using a smaller set of functions, and a simpler diagnosis criterion. Moreover, the earthquake catalogues may include lower magnitudes than in algorithm CN.

However, both algorithms are referred to intermediate-term earthquake prediction and have been tested on independent data. The algorithm CN has been successfully applied to several regions of the world (Allen et al., 1983; Keilis-Borok et al., 1988; Keilis-Borok et al., 1990). The algorithm M8 has also been applied to 19 different regions of the world and the results can be summarized as follows: TIPs precede 27 out of 34 strong earthquakes and, in different regions, occupy, on the average, about 24% of the time interval annualized.

For the area of Greece, and especially along the Hellenic arc several studies have been made to investigate the seismicity patterns, including seismic gap, drop of seismicity rate, inactivity of the seismogenetic layer, seismic periodicity (Wyss and Baer, 1981a,b; Papazachos and Comninakis, 1982; Purcaru and Berkchemer, 1982; Papadimitriou and Papazachos, 1985; Papadopoulos 1986, 1988). However, Ambraseys (1981) pointed out, at that, that the limited data on spatial and temporal variations in seismicity in the Hellenic arc do not seem to justify specific predictions. It is noteworthy that all previous studies have been based on historical and instrumental data by using only large or moderate earthquakes, and that, the occurrence time of the forthcoming large earthquake along the Hellenic arc was given in the long-term sense, i.e. next decade or so.

On the other hand, the algorithm M8 depicts the activation of the earthquake flow in the lower magnitude range. A TIP is declared when (i) all the characteristic functions are defined and (ii) all the functions achieve large values during a common time interval. To fulfil the first condition at least six years of data from the beginning of the catalogue are needed to distinguish long seismicity level from a short one.

Therefore, the application of the algorithm M8 to the area of Greece and especially to the Hellenic arc by using solely recent complete regional data from 1971 onwards will essentially contribute to earthquake prediction problem in this region.

OUTLINE OF THE ALGORITHM M8

For convenience of the reader, we briefly repeat the functions which are used in the algorithm M8. More details are given by Keilis-Borok and Kossobokov (1986).

The functions are defined on a sequence of main shocks. Each main shock is defined by the vectors of six components. (t_i, φ_i, λ_i, h_i, M_i, $B_i(e)$), where i is the sequence number of the main shock, t is the origin time, φ is the latitude, λ is the longitude, h is the focal depth, M is the earthquake magnitude, and B(e) is the number of aftershocks that occurred in the first e days after the main shock.

The function N(t:m,s) defines the current level of seismic activity, in other words it depicts the number of main shocks with M≥m in the time interval (t-s,t).

The function K(t:m,s) defines the increment of seismic activity and is given by:

$$K(t:m,s) = N(t:m,s) - N(t-s:m,s)$$

The function V(t:m,s) defines the variation of the seismic activity and is given by:

$$V(t:m,s,u) = \Sigma[N(t_{i+1}:m,s)-N(t_i:m,s)]$$

The function $L(t:m,s,t_o)$ defines the deviation of seismic activity from a long-term linear trend and is given by:

$$L(t:m,s,t_o)=N(t:m,t-t_o)-N(t-s:m,t-s-t_o)(t-t_o)(t-s-t_o)^{-1}$$

The concentration of main shocks in space is defined in the following way. Let $S(t:m,M',s,\alpha,\beta) = \Sigma 10^{\beta(Mi-\alpha)}$ be a weighted sum of the main shock within (t-s,t) time and (m,M') magnitude intervals. Each weight depends on the magnitude and is roughly proportional to the length of source. Specifically, we have used β=b/3, where b is the coefficient in the magnitude energy relation logE=a+bM. The parameter a normalizes the weights. The average length of a source is proportional to S/N, and the average distance between them is proportional to $S/N^{-1/3}$ in the case of uniform distribution. Their ratio characterizes concentration and can be roughly estimated by the function

$$Z(t:m,M',s,\alpha,\beta) = S(t:m,M;,s,\alpha,\beta)/[N(t:m,s)-N(t:M',s]^{2/3}$$

The function B defines the clustering of earthquakes and $B(t:m,M',s,M_o,e)$ is the maximal number of aftershocks with $M \geq M_o$ in the first e days after a main shock within intervals (t-s,t) and (m,M').

Because the seismic activity in the regions considered is obviously different, we normalize it by adjusting the magnitude threshold M so that the average yearly rate(number) of occurrence of main shocks with M≥m in an area is equal to a certain common value. For one set of functions designated as N_1,L_1 and Z_1 the constant is 10 per year, and it is 20 per year for another set N_2,L_2, and Z_2,i.e. for two levels of seismicity 1 and 2. For all these six functions the duration of a time interval s is 6 years. The upper magnitude threshold M is defined to M_0. For the function Z we have used $M'=M_0-0.5$. For B the threshold were $m=M_0-2$ and $M'=M_0-0.2$.

To diagnose a TIP at time t we require that over the preceding 3 years:

(i)each group $\{N_1,N_2\}$,$\{L_1,L_2\}$,$\{Z_1,Z_2\}$,{B} contains functions with extremely large values, and

(ii)at least 6 out of 7 functions $\{N_1,N_2\}$,$\{L_1,L_2\}$,$\{Z_1,Z_2\}$,{B} have extremely large values concurrently. Extremely large refers to values in the upper Q% quantile range (Q=25 for B and Q=10 for all other functions, i.e. in the 10% larger values).

Finally, the vector $F_\mu(t)$ of the above mentioned functions is computed for discrete times $\{t_i\}$ with a half-a-year step. The time interval $(t_i,t_i+\tau)$ is a TIP when the conditions (i) and (ii) occur at t_{i-1} and t_i.

PREVIOUS RESULTS

For the area of Greece and adjacent territories the algorithm M8 has been applied for M_0 = 7.0 (Latousskais and Kossobokov, 1990). It has been revealed, retrospectively, that the three strongest earthquakes of M_S≥7.0 which occurred in Greece during the time interval 1973-1988 were preceded by a specific increase of the earthquake activity in the lower magnitude range which was depicted by the algorithm M8.

Furthermore, for the same area an attempt was made by Latoussakis and Stavrakakis (1992) to investigate whether the algorithm M8 could be applied to smaller earthquakes, i.e M_L≥5.5 which are of major practical importance due to their frequent occurrence in the area of Greece. The obtained results seem to be promising in terms of intermediate-term earthquake prediction.

Especially, the above authors examined 15 earthquakes of M_L≥5.5 which took place in Greece and surrounding region from 1977 to 1990. Ten of them occurred within TIPs. The algorithm failed in diagnosing TIPs in four cases, because the relevant events occurred in regions, i.e. Albania, West Turkey, for which a complete earthquake catalog was not available to the authors. Only in one case, namely that of Thessaloniki (northern Greece) earthquake of June 20, 1978 the algorithm M8 did not diagnose any TIP. It might also be explained in terms of the completeness of the National Observatory catalog for northern Greece at that time. This fact indicates how critical the selection of the area is, within which TIPs are sought.

Once we have examined the applicability of the algorithm M8 to smaller earthquake in Greece, we continue to explore the possibility of identifying current TIPs of occurrence of earthquakes with M_L≥5.5 for the same area. The obtained results are discussed in terms of the seismic history of the regions.

APPLICATION OF THE ALGORITHM M8

As we mentioned above, by considering a threshold magnitude M_o, equal to 5.5 then the algorithm M8 requires complete data for events with magnitudes M_o-2 (i.e. 5.5-2=3.5) and above. In the present study we used the NOA catalog which is complete for earthquakes with $M_L \geq 3.2$ for the time period 1971-1990. This catalogue contains about 14,000 earthquakes with local magnitude in the range 3.0 to 6.8 for the above mentioned time period. Fig. 1 shows the epicentre distribution of the events with $M_L \geq 4.5$ which occurred in Greece and adjacent region form 1971-1990. Since the algorithm M8 requires main shocks, we remove the aftershocks from the catalogue following the criteria given by Latoussakis and Stavrakakis (1992).

After that, the territory (31°-41°N, 21°-27°E) was firstly scanned by overlapping circles of diameter D = exp(M_o-5.6)+1 in degrees of the Earth meridian, that is a radius of 105km for a M_o=5.5, with a step of one degree in latitude and longitude, respectively. The seismicity is considered within each area, and several integral traits of an earthquake activity are estimated as functions of a sliding time window. If most of them (at least six out of seven) become extremely large within a certain narrow time interval a TIP is diagnosed for 5 years. In light of the above first scanning of the territory, by 72 overlapping circles, a first diagnosis of TIPs for M_o = 5.5 was done.

The results have shown that 14 circles (see fig.2) contain current TIPs. These circles delineate four volumes as illustrated in fig. 2 and we look for the stability of the diagnosis for each volume separately as follows.

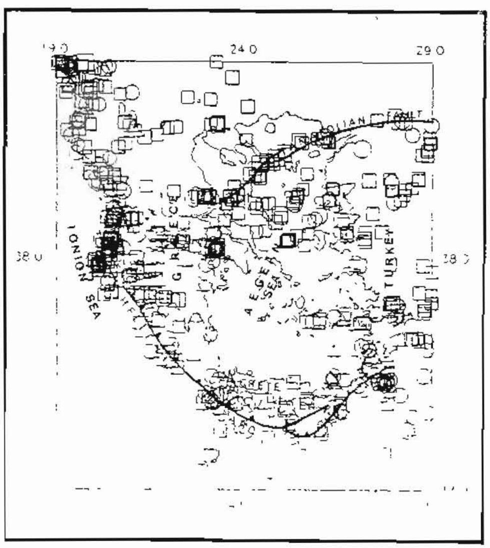


Fig.1. Epicentre distribution of earthquakes with M_L>4.5 for the time period 1971-1990 (NOA's catalogue).

(a) Volume I (Southwestern Aegean Sea Region)

In this volume, the TIP has already been filled. Latoussakis and Stavrakakis (1992) have found the diagnosis of a TIP in southwestern part of the Hellenic arc. These authors have pointed out that this TIP is expected to be filled by the end of 1992, by an earthquake of magnitude $6.0 \le M_0 \le 7.5$. Actually, on Nov., 21, 1992 a strong earthquake of M_s=6.5 took place within the TIP. We believe that this event was successfully predicted in terms of capability of the algorithm M8 (intermediate term earthquake prediction). It should also been emphasized that during the 1st Workshop on "Statistical Methods in Seismology-Applications on the Prevention and Forecasting Earthquakes" held in Athens (27-29 Nov., 1991) we presented the results obtained for the Hellenic arc. In the abstract volume figures 3a and 3b are included which showed the candidate area for the forthcoming event.

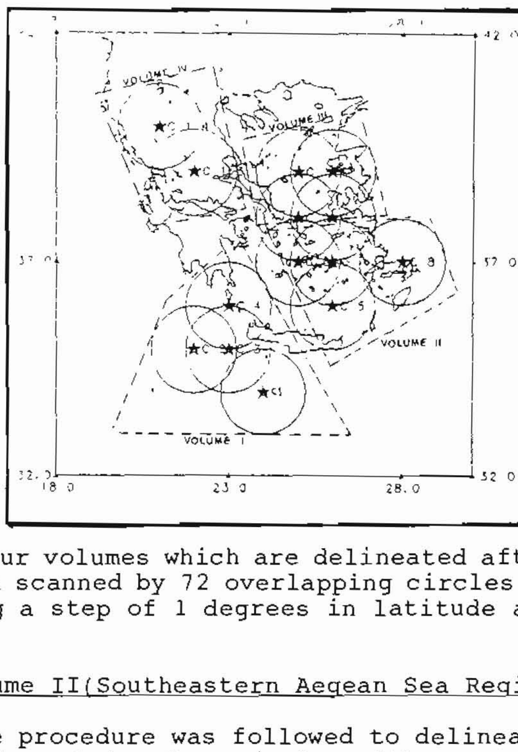


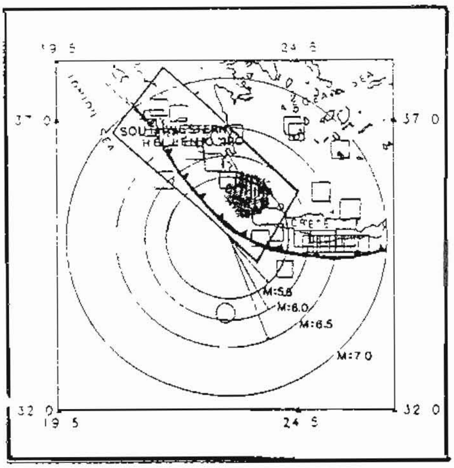
Fig.2. The four volumes which are delineated after the territory had been scanned by 72 overlapping circles of radius of 105 km using a step of 1 degrees in latitude and longitude.

(b) Volume II(Southeastern Aegean Sea Region)

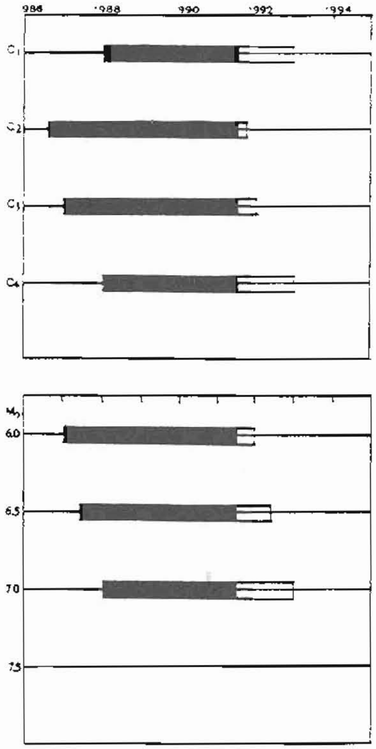
The same procedure was followed to delineate the volume II (fig. 2) which contains four circles with centres C5(36°N,26°E), C6(37°N,25°E), C7(37°N,26°E) and C8(37°N,28°E) and of radius equal to 105km (M_0=5.5).

Furthermore, the volume II was scanned by overlapping circles (fig. 4a) with a centre the geographical centre of C5,C6,C7,C8 and of various radius corresponding to higher M_0 in order to investigate whether TIPs appear in this region for higher magnitudes. Again, it does not mean that four earthquakes will follow the TIPs. Actually, one current TIP was diagnosed and the different circles delineate the candidate areas for different magnitudes. Figure 4b shows the obtained results. For $M_0>7.0$, no TIP was identified, indicating probably an upper bound magnitude for volume II.

Based on the spatial distribution of the large events(fig. 4a), and by considering the conclusion made by WYSS and BAER(1981a,b) it is reasonable to consider as the most probable location near 36.5°N- 27.5°E (broad region of Kos island) with a surface magnitude $6.0<M_s<7.0$. It is of great importance to emphasize at this point, that an abnormal nucleation of subcrustal earthquakes in the vicinity of Kos island has been observed for the time period 1971 -1985 (GALANOPOULOS, 1989). Especially, during the above time period, 57 out of 122 events of $m_b > 3.0$ and with focal depths greater than or equal to 100 km occurred in the vicinity of Kos island. In several cases it has been reported that deep-focus earthquake activity sometimes increases preceding large shallow earthquakes (MOGI, 1973). We consider this observation as an additional fact which enhances our estimation for the location of the earthquake expected to occur in the southeastern part of the Hellenic arc.



(a)



(b)

Fig.3. (a) Large earthquakes occurred in the southwestern part of the Hellenic arc for the time period 1500-1987 (Papazachos and Papazachos, 1989). The shaded area depicts the most probable location for an impending earthquake. (b) Current TIPs for Volume I.

(c) Volume III (North - Central Aegean Sea Region)

This region (fig.2) was also delineated by following the same procedure as above. It contains four circles with centers C9(38°N-25°E), C10(38°N-26°E), C11(39°N-26°E), and C12(39°-26°E) and of radius equal to 105 km (M_0=5.5). Each circle contains a TIP. The results are shown in figures 5a and 5b. Based on the spatial distribution of the large events and by considering the seismic history of this region, we speculate as the most probable location near 38.5°N-25.5°E for a shallow earthquake of surface magnitude 6.0 < M_s <7.0.

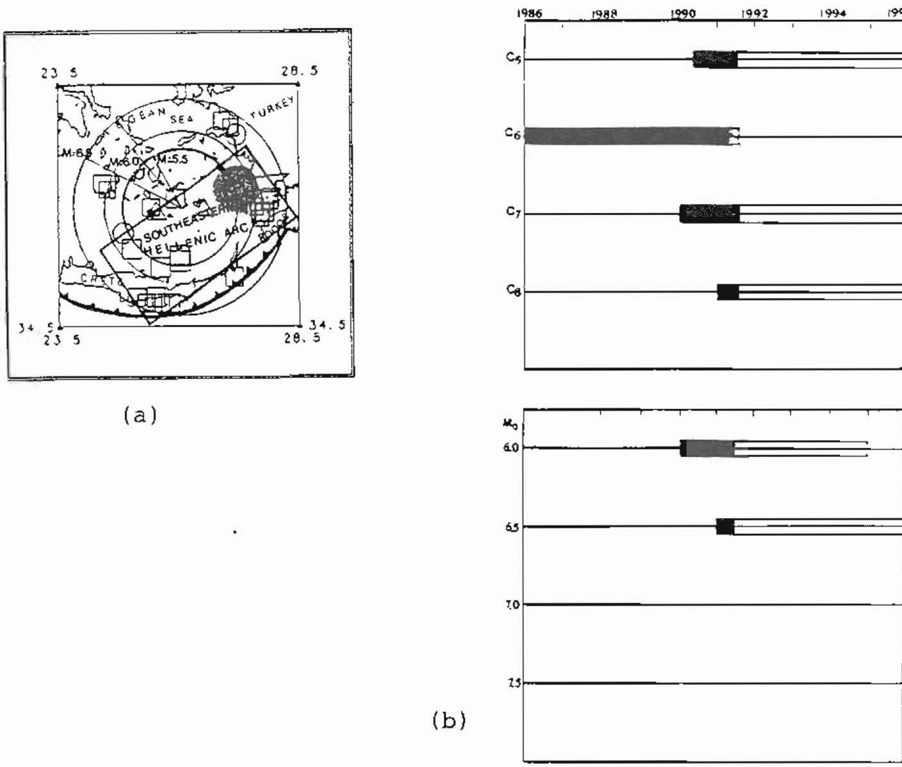
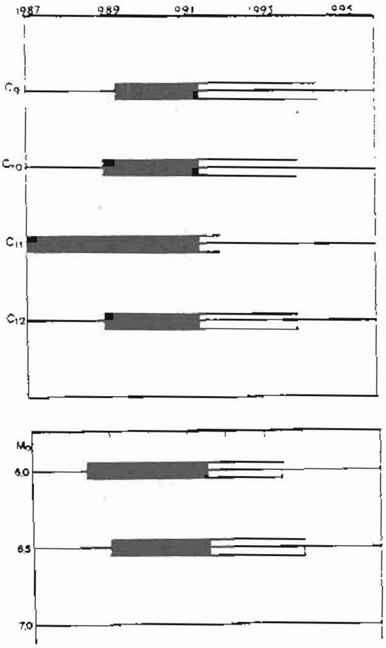


Fig.4. The same legend as figure 3a and 3b, for the southeastern part of the Hellenic arc (Volume II).

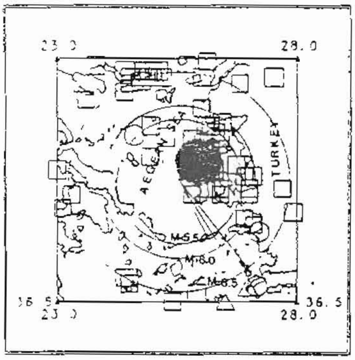
(d) Volume IV (Mainland of Greece)

Tis volume (fig.2) is delineated by two circles with centers C13(39°N-22°E) and C14(40°N-21°E) and of radius equal to 105 km (M_0=5.5). To ensure that the current TIPs do not appear by random, the volume IV was also scanned by overllaping circles with centers 39.5°N - 21.5°E, and various radii corresponding to higher magnitude thresholds. The results are shown in figures 6a and 6b. When M_0 >6.5 the TIPs were not identified. It is evident that the characteristic earthquake magnitude M_0 for which current TIPs were not diagnosed is different for each volume indicating also a different upper bound magnitude consistent with the seismic history of each region. Furthermore, it might indicate the present seismic potential of each volume.

By a further consideration of the seismic history of the region we expect as a probable location near 39°N-22.5°E for the forthcoming earthquake of surface magnitude 6.0 < Ms <7.0.



(a)



(b)

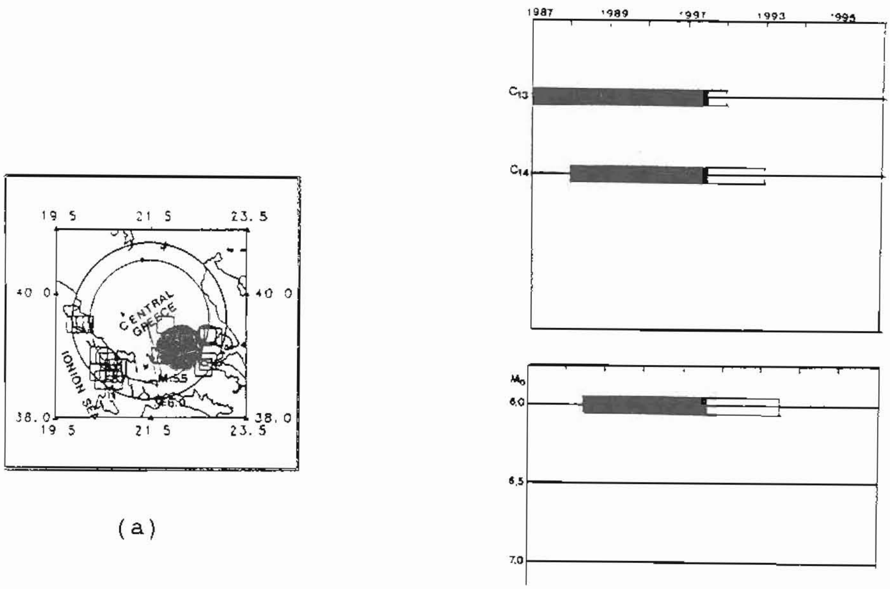
Fig.5. Same as legend of figure 3a and 3b for Volume III.

DISCUSSION AND CONCLUSIONS

Once the applicability of the algorithm M8 has retrospectively been tested for earthquakes of $M_0 \geq 5.5$ occurred in Greece, we further explored the possibility of identifying current TIPs for this area. For this purpose, the territory was scanned by overlapping circles of radius equal to 105 km corresponding to a $M_0 \geq 5.5$. In this way, a first diagnosis was made aiming at delineating subregions for which current TIPs are sought by considering higher magnitudes M_0 and different seismicity parameters.

Volume I includes the southwestern part of the Hellenic arc for which current TIPs were diagnosed for M_o=5.5, to 7.0. For higher magnitudes no TIP was found indicating, probably, the present seismic potential of this region. For this region we expected a large event by the end of 1992. Details of this intermediate term earthquake prediction was published by LATOUSSAKIS and STAVRAKAKIS (1992).

As far as the location of the forthcoming large earthquake within the current TIP is concerned, it was significantly reduced by considering the seismic history of the investigated region. As we have pointed out the probable location was the area between Anticithira island and off the western coast Crete, and not anywhere within the circles of fig.2. Actually it happened on Nov.21, 1992 with the occurrence of the M=6.5 event.



(a)

(b)

Fig.6. Same as legend of figure 3a and 3b for Volume IV.

Volume II includes the southeastern part of the Hellenic arc for which a current TIP was also diagnosed, but for smaller magnitude (M_o=6.5) of the impending earthquake. It might be an indication that the seismic potential of the western part of the Hellenic arc is higher than that of the eastern one. It is also interesting to notice that the current TIP for M_o=6.5 in this region started very recently (at the beginning of 1991) in contrast to the TIP for the west Hellenic arc. By considering the seismic history of this region, especially the recent abnormal nucleation of deep focus earthquakes in the vicinity of Kos island, we assume this area as candidate one for the next large earthquake in the East Hellenic arc.

For volumes III and IV, current TIPs were also declared for $M_0 \geq 6.5$, and 6.0, respectively. Also in these cases, the locations expected of the forthcoming large earthquakes were given in terms of the seismic history of the relevant regions.

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