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Qualitative Precursory Seismicity Pattern in Greece: Practical Tool for an Impending Strong Assessment

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***Abstract*— The temporal variation of the seismicity based on the analysis of three seismic parameters i.e., number of earthquakes, b-value and energy released establish a precursory seismicity pattern. The estimates of the parameters were obtained by the means of a new analysis tool suited to analyze earthquake catalog and to visualize their spatio-temporal variation behavior, in a given area and time period. The obtained temporal variation series in the overwhelming majority of the examined cases have shown significant changes before the strong earthquake occurrence, so that they can be considered as precursory anomalies. The correlation found between these anomalies and strong earthquake shows a remarkable temporal regularity so that this can be formulated as precursory seismicity pattern. This result suggests that the continuous monitoring of the temporal variation of the seismic parameters and the interpretation of the formed temporal pattern, can contribute to the assessment of the impending strong earthquake in a given area.**

Keywords*— *temporal variation of seismicity; precursory seismicity pattern; earthquake prediction

I. INTRODUCTION

Precursory seismicity parameters changes have attracted the attention of many researchers over the years, mainly based on the knowledge that some basic seismic parameters were considered as earthquake precursors. Thus in several cases these temporal variation changes, prior large earthquakes, was reported by several researchers worldwide (Smith, 1981; Imoto, 1991; Sobolev et al., 1991; Ponomarev et al., 1997; Zavyalov, 2002; King and Bowman, 2003; Enescu and Ito, 2001; Monterosso, 2003) and in Greece as well (Papadimitriou and Papazachos, 1985; Papadopoulos et al., 2002). However without establishing a firm and regular pattern in space and time.

Papadopoulos and Baskoutas (2009; 2011) and Baskoutas et al., (2007; 2011) analysing seismic data from the earthquake catalog, in different areas and time periods have observed a remarkable regularity, of the seismic parameters temporal behavior, prior the occurrence of strong earthquakes, so that they can establish a seismic precursory pattern.This pattern was interpreted in terms of an earthquake preparation seismic cycle and accordingly in stages of the examined seismicity parameters temporal variation behaviour.

Aim of this study is to examine the characteristics of the proposed seismic precursory pattern, as a tool, for the assessment of the impending strong earthquake probability level.

II. SEISMIC PARAMETERS DEFINITION AND ANALYSIS

Details of the FastBEE algorithm, as well as, the method of the seismic parameters calculation can be found in Papadopoulos and Baskoutas (2009; 2011). Although for the better understanding of the present paper follow the short description of the seismicity parameters definition i.e. number of earthquakes per unit time, b-value estimates, and seismic energy released, as well as short description of the analysis.

Estimates of the number of earthquakes per unit time are obtained in the form logN(t), equation (1).

$$\log N(t) = \log\left(\sum_{i=t-w}^{n(t-w)} i\right) \tag{1}$$

where i is the number of earthquakes, with magnitude $Mw > M_{\min}$, $M_{\min}$ is the minimum magnitude of the catalogue completeness, in a given area and time interval, t is the time interval of one month, w is the length of the smoothing (filter) window, $n(t\text{-}w)$ is the number of earthquakes in the smoothing window time interval. The standard error of the calculation is given by the relation: $\sigma_{\lg N}=0{,}4343/\sqrt{N}$

The estimates $b(t)$ of the b-value were calculated by the maximum likelihood method and the follow relationship (2):

$$b(t) = \log\left[1+\frac{\mathrm{N}_\Sigma(t-w)}{\sum_{i=0}^{n} i\cdot \mathrm{N}_{M_{\min}+i\Delta M}(t-w)}\right] \Big/ \Delta\mathrm{M} \tag{2}$$

where N_Σ is the total number of earthquakes, with magnitude $M_w > M_{\min}$, $M_{\min}$ is the minimum magnitude of the catalogue completeness, in a given area and time interval, $N_{M\min+i\Delta M}$ is the number of earthquakes in the ith magnitude, $n=1+(M_{\max}-M_{\min})/\Delta M$ is the number of the increment $\Delta M=0.20$. The standar error of the b-value estimates is obtained by means of the relation: $\sigma_b(t)=b(t)/\sqrt{\mathrm{N}_\Sigma}$

Finally the parameter $\log E^{2/3}$ which represents the mean seismic energy released in the time unit is obtained by the relation (3):

$$\log E^{2/3}(t) = \log\left(\frac{1}{n(t-w)}\sum_{i=t-w}^{n(t-w)} E_i^{2/3}\right) \qquad (3)$$

where t is the time interval of one month, n(t-w) –is the number of earthquakes in the smoothing window time interval. E_i is the seismic energy of the i^{th} earthquake in the time window w, which, for Greek territory, is equal to $10^{1.5Ms+4.7}$ (Papazachos and Papazachos 2000a). The confidence limits were calculated in the range of the examined time period and they were considered as a measure of the statistical significance.

III. TEMPORAL VARIATION ANALYSIS

Temporal variation series of the seismic parameters estimates were obtained by a simple moving-window technique with a user defined window length and one-month step, which were then filtered so that temporal changes, with periods equal or greater of the half filter width are more evident (Jenkins and Watts, 1968).

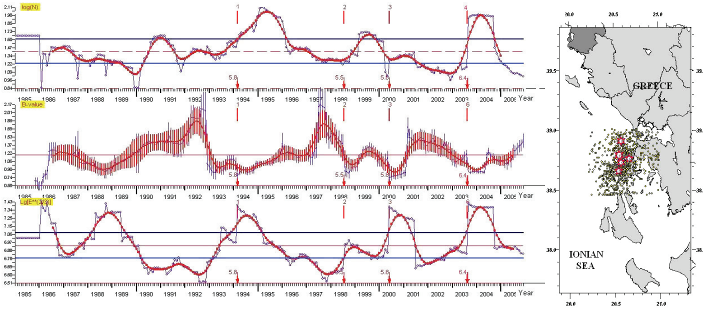

Figure 1. FastBEE temporal variation analysis of the seismic parameters in the case of 2003, Aug 14, M= 6.4 Leukada earthquake (left) and the respective seismic epicenters map with data used in the analysis (right). The red star shows the earthquake epicenter.

Figure 1, shows an example the typical visualization output window of the FastBEE tool (left side of figure 1), for the period 1985-2005 including the case of 2003, August 14, Ms= 6.4 Leukada earthquake. In the right side of the same figure, can be sheen the spatial distribution of the epicenters of the seismic events used in this analysis. This data set was taken from the monthly bulletin of the Geodynamic Institute of the National Observatory of Athens and its magnitude completeness Mmin=3.2. In this figure, the curves of the temporal variation of the seismic parameters, logN(t), b-value and $\log E^{2/3}$, are shown from the top to the bottom, as a complex of two superposed curves, i.e. a the first thin blue curve represents the smoothed time series and the second bolder red line the filtered one. Standard errors for the b-value and the confidence limit 1σ of the parameters logN and $\log E^{2/3}$, as lines parallel to their mean values in the examined time period, can be shown also in the same figure.

The origin time of all strong earthquakes with a magnitude equal or greater than a given threshold, (in this example M≥5.5) occurred in the examined area, are marked with numbered arrows perpendicular to the time axis. Their catalog parameters are reported in the Table I.

TABLE I. LIST OF EARTHQUAKES AND THEIR RESPECTIVE CATALOG PARAMETERS

Year	Mon	Date	Origin Time	Cordinates		Dept	Magnitude(Ms)
1994	FEB	25	02 30 49.7	38.73	20.58	5	5.8
1998	JUL	16	17 29 16.7	38.66	20.55	5	5.5
2000	MAY	26	01 28 22.0	38.91	20.58	5	5.8
2003	AUG	14	05.14 53.9	38.79	20.56	12	6.4

This magnitude, defined as Minimum Prognostic Magnitude represents the lower magnitude threshold that fit better the characteristic temporal fluctuations, which were observed in the seismic parameters temporal variation. Physically, this magnitude represents the typical response of the medium to the elastic deformation in the examined period. The greater the observation time, the more representative the response is, revealing the seismotectonic characteristics of small regions under the influence of broader regional stress.

IV. PRECURSORY SEISMICITY PATTERN

The careful inspection of the observed clear fluctuation of all parameters, over and above their relative mean values, forms consecutive relative minima and maxima. These changes, although their qualitative characters are believed to reflect the changes in stress in the broader area.

The positive relation of the observed significant fluctuations with strong earthquakes occurrence were considered by Papadopoulos and Baskoutas (2009; 2011) as prognostic anomalies. The regularity of temporal prognostic anomalies appearance, over a long time variation profiles can be formulated, in the ambit of the FastBEE algorithm, as a qualitative precursory seismicity pattern. The general trend of this pattern, in all three parameters, appears schematically in the figure 1 and its characteristics can be summarized as follow:

The temporal variation of the parameter logN, shows, in the majority of the cases a clear decreasing phase toward to the relative mean value, in the examined time interval and bellow to the confidence level of 70%, reaching to a relative minimum. Usually the relative mean values, especially when the examined time interval is long enough, some how represent the background ("normal') seismicity of a given region and the previously decreased behavior denote kind of "quiescence" period. This parameter usually reflects the fluctuation of the number of earthquakes despite the present or the absence of a strong earthquake. In case of strong earthquake occurrence the influence of its aftershock activity can add information of the evaluation of the two other considered seismic parameters. In all examined cases, the preceded smaller magnitude events have not aftershock activity, in order to attribute the observed prognostic anomalies, in such kind of activity. Moreover it was found that the use of a declustered, for aftershocks, earthquake catalog doesn't change the qualitative character of the observed precursory seismicity pattern.

Parameter b-value instead shows at the beginning an increasing trend until it reaches a relative maximum. After that, this parameter starts to decreases constantly toward to the relative mean value and even lower. Usually the strong earthquake occurrence coincides within this time interval and mostly at its later stage.

Finally, the fluctuation of the parameters logE2/3, in similarity with parameter logN and contrary to the b-value behavior, is characterized by a gradual decrease toward to the relative mean value and even lower to the confidence limit. The inversion of this trend to toward to the mean value, signalize the impending strong earthquake occurrence.

It was observed that the temporal evolution of the foresaid prognostic anomaly can be divided in two distinct temporal stages. During the time evolution of the first stage, the probability for a strong earthquake occurrence is very low, contrary with the beginning of the second stage the probability increases signalizing thus an alarm period. As the temporal anomaly is approaching to its end the probability of occurrence became higher (dashed line in figure 2). Among the three examined seismic parameters it was also found that b-value and the seismic energy releases in the form logE2/3 are more informative in respect to the parameter logN, although this last can add information when anomalous temporal variation appears in the seismicity of the region. Nonetheless parameter logE2/3 seems to describe much better the observed temporal variation of the seismicity due to the temporal changes of the stress field influence, since this situation can be expressed better in the ambit of relatively greater size earthquake magnitudes i.e. greater than 3.5 -3.8 those of smaller one.

The temporal variation of the quantity logN(t), although it doesn't always show the foresaid clear relation as the two other parameters, in the majority of the cases also passes a relative minimum, before the occurrence of a strong earthquake, indicating somehow a seismic quiescence.

According to the temporal behaviour the future strong earthquake occurrence assessment requires the identification of this pattern and its further inspection. This procedure usually starts with the investigation of large scale areas and going on with smaller one, by repeating trials and using different duration filters windows. Once a candidate area is defined then the continuous monitoring of the temporal variation anomalies evolution is needed, using the FastBEE tool analysis. According to the previous findings, the occurrence time of an impending earthquake can be expected during the time evolution of the second phase of the observed anomaly. The probable magnitude as well the future earthquake location assessment can be weighted taking into consideration the definition of the minimum prognostic magnitude, which characterises the area, taking for analysis the longest period complete catalogue, the seismic potential of the examined area, in terms of maximum expected magnitude in several return periods as well all available geotectonic or other information.

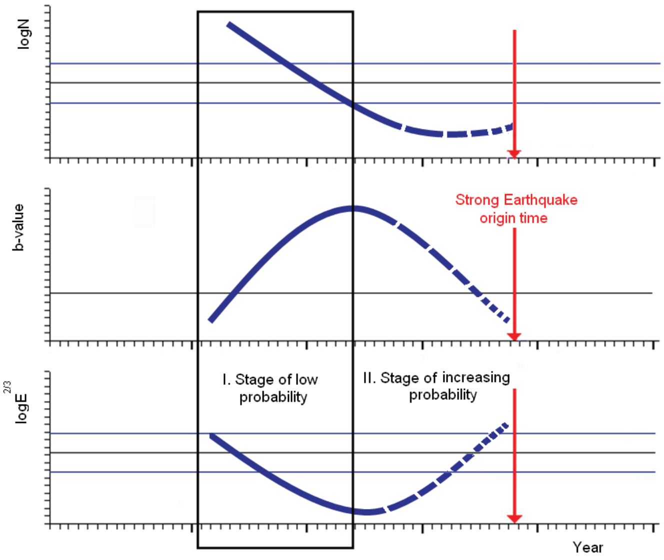

Figure 2. Schematic trend of a temporal prognostic anomaly (solid blue lines) before a strong earthquake occurrence, according to the FastBEE output. Open rectangular parallelogram denotes the first, low probability stage, since the prognostic anomaly beginning. The following period of the increasing probability. Vertical red arrow shows the earthquake origin time.

V. CONCLUSIONS

The temporal variation analysis of a set of three seismicity parameters, with FastBEE algorithm, have brought into light precursory seismicity pattern which may not be immediately apparent in strictly quantitative data analysis methods.

The obtained temporal variation profiles of the seismicity, shows clear fluctuations, with repeated characteristic changes around relative mean values, which can be related to the strong earthquakes occurrence. These changes were considered as temporal anomalies and their correlation to the strong earthquakes was formulated in a qualitative character precursory seismicity pattern. The occurrence of an impending strong earthquake can be estimated few months to two year after beginning of the anomaly.

Moreover the time evolution of the precursory stage can be assessed by the constant monitoring the temporal variation profile of the seismicity parameters, in a given area and can act as an alarm signal for an impending strong earthquake occurrence, even if the correlation appears in the earlier or later stage of the second phase of the observed anomaly.

Although the duration of such qualitative precursory anomalies it is not proportional to the earthquake magnitude and their shape and sides vary from case to case, the characteristic distinction in two probability stages can be still useful for the identification of the beginning alarm period.

Some times the correlation is weak or it refers to a burst of events. Both observations may reflect the effect of the geotectonic environment and the geodynamic regime, which influence the earthquakes occurrence, delaying or accelerating its origin, although we don't know exactly how. Nevertheless analysis of a common earthquake catalogue data, by means of

FastBEE tool, can reveal precursory pattern. The continuous monitoring of the temporal variation of the seismicity and especially the temporal evolution of the formed temporal anomalies can contribute the seismic danger assessment, in different seismogenic areas.

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