

ON THE INVESTIGATION OF CAUSAL RELATIONS BETWEEN SEISMIC SERIES

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Abstract

The Aegean and the surrounding area is considered as the seismically most active region in Europe. The separation of this area into nineteen seismic zones has been based on the distribution of the epicentres as well as on other seismotectonic criteria. In this paper two methods are employed for the investigation of causal relations between the 19 zones. Cross-correlation techniques are applied and linear intensity models are fitted in order to give a mathematical description of the earthquake occurrence in one of every two of the 19 zones, given the seismicity of the other one. Model selection criteria such as Akaike's Information Criterion, are used to estimate the parameters of the intensity models. Finally, the results are compared and the most interesting cases are presented.

Keywords and phrases: Plate Tectonics; Seismicity; Cross-correlation; Intensity functions; AIC.

1. Introduction

The theory of Plate Tectonics is based on the idea that the Lithosphere is divided into large, not flexible parts, the lithospheric plates, which slowly move relatively to each other

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causing deformities mainly near their edges. It is believed that 99% of the world seismicity occurs near the lithospheric edges.

The Aegean and the surrounding area (34°N-43°N, 18°E-30°E) that includes Greece, Albania, southern Yugoslavia, southern Bulgaria and western Turkey, is considered as the most seismically active regions in Europe. The main reason of the intensive seismic activity is the convergence of the Eurasian and African plates. In particular, the northern part of the African plate penetrates the Eurasian plate and by moving anti-clockwise it collides with the Eurasian plate along Yugoslavia, Albania and North-western Greece, causing mainly, shallow earthquakes. Furthermore, the northern part of the African plate consists of the oceanic lithosphere of East Mediterranean whilst the Eurasian plate is continental. Their convergence results in the subduction of the former along the Hellenic arc that is situated in southern Greece and Aegean. Finally, the Turkish microplate which is part of the Eurasian plate and moves to the west, is responsible for the well known North Anatolian fault. It is believed that when this fault enters the Aegean sea is separated into parallel faults.

Although many authors (Papazachos, 1990, Hatzidimitriou, *et al.*, 1994, Papadopoulos, *et al.*, 1986) have successfully described and explained the seismicity of the area under study, earthquake prediction is still a complex problem. The process of earthquake generation and the reliability of the available data are some of the difficulties that indicate the need to use probabilistic models in order to formulate earthquake occurrence. As the protocol of UNESCO and IASPEI (International Association of Seismology and Physics of the Earth Interior) proposes, 'predictions should be formulated in terms of probability, i.e. the expectation in the time-space-magnitude domain of the occurrence of an earthquake' (Vere-Jones, 1995).

The scope of the present study is to investigate the causal relations that possibly exist between the seismic zones of the Aegean and surrounding areas. Nineteen such zones have been defined according to the distribution of the epicentres, the seismicity levels, the type of faulting and other criteria (see Figure 1). Most of them consist of two or more subzones giving a total of 69 areas of shallow earthquakes. Cross-correlation techniques and the stochastic point process theory have been employed for the formation of the causal influence between two seismic zones. Both methods have been applied on every possible combination of the 19 zones and the results have been compared and discussed.

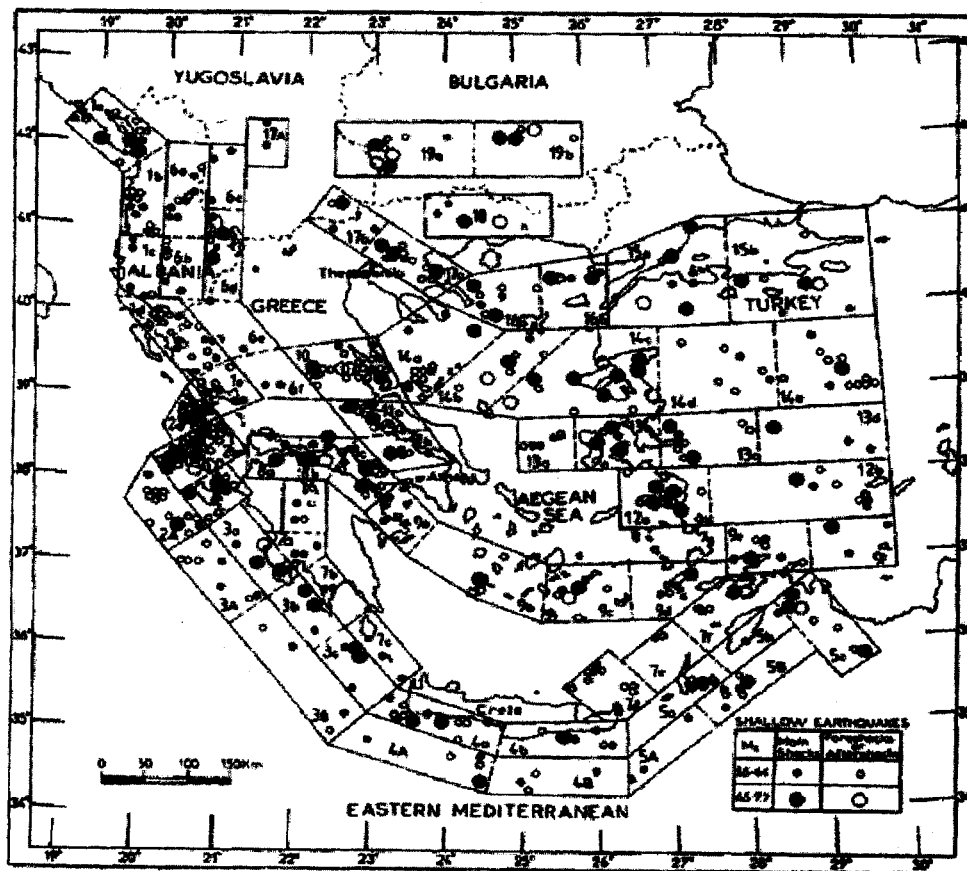


Figure 1. The 69 subzones of shallow earthquakes in the Aegean and surrounding area (Papazachos and Papaioannou, 1993).

2. Earthquake Catalogues

The earthquake catalogue used in this study is published by Makropoulos (Makropoulos and Burton, 1981, Makropoulos, *et al*, 1989) and it covers the period 1900-1987. It contains 4988 shallow shocks for which the following parameters are listed: Date (year, month, day), Origin Time (hour, minute, second), Latitude, Longitude, Focal Depth, Magnitude (M_s).

Any earthquake catalogue is considered valid and useful only if it is complete above a certain magnitude and homogeneous. Makropoulos' catalogue satisfies both criteria. Results from the test of completeness for Greece listed in Table 1 show that as time passes the threshold magnitude above which the events are completely reported goes down.

Magnitude	Period of completely reported events
$M \geq 4.0$	1976-1987
$M \geq 4.5$	1950-1987
$M \geq 5.0$	1940-1987
$M \geq 5.5$	1911-1987
$M \geq 6.0$	1900-1987

Table 1. Results from the test of completeness

On the contrary, the earthquakes' distribution according to their magnitude Figure 2, shows that as the threshold increases the number of shocks decreases.

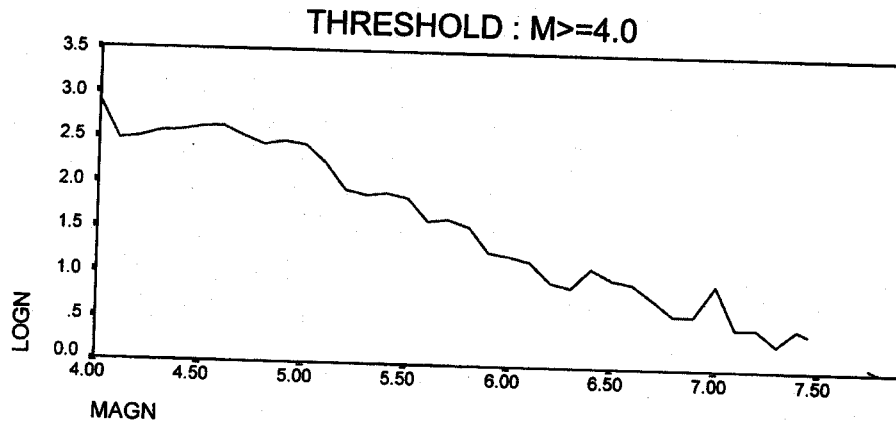


Figure 2. Frequency distribution according to magnitude

3. Cross-Correlation

3.1 Data and Method

It is well known that the seismicity of an area is a function of the magnitude of the earthquakes and their frequency of occurrence. For the quantitative analysis of the seismicity, the energy released (E) from each shock has been calculated according to the following formulas (Skordas, *et al*, 1991):

$$\text{For } M \geq 5.0 \quad \log E = 12.24 + 1.44 M \quad \text{For } M < 5.0 \quad \log E = 11.72 + 1.68 M \quad (1)$$

The anti-logarithms of the annual sums of the seismic energy released in each zone separately, are the data used for the estimation of the cross-correlation coefficients defined as (Chatfield, 1989):

$$r(\tau) = C_{xy}(\tau) / \sqrt{s_x^2 s_y^2}$$

where

$$C_{xy}(\tau) = \begin{cases} \frac{\sum_{i=1}^{N-\tau} x_i y_{i+\tau}}{N-1} & \tau = 0, 1, \dots, N-1 \\ \frac{\sum_{i=1-\tau}^N x_i y_{i+\tau}}{N-1} & \tau = -1, -2, \dots, -(N-1) \end{cases}$$

x_i, y_i , centered observations of the zero mean time series

s_x^2, s_y^2 , sample variances for x and y , respectively

N , number of observations in each of the two time series

τ , time lag that varies between -15 and +15

3.2 Application and results

Before presenting the results, some explanations are given:

The absence of seismic events during a given year is denoted by 0 (zero energy released) which may not be totally realistic since earthquakes of $M < 4.0$ are not reported. On the other hand, according to (1) small events contribute very little. Zone 18 was excluded because of its insufficient number of observations. Negative coefficients are meaningless and generally, we are interested only in coefficients greater than 0.5 which correspond to small time lags ($-4 \leq \text{lag} \leq 4$). Pairs of zones that meet the above requirements are listed below:

zones 1 and 2	zones 4 and 9	zones 10 and 12	zones 2 and 15
zones 2 and 4	zones 2 and 10	zones 2 and 13	zones 9 and 15
zones 3 and 5	zones 9 and 10	zones 3 and 13	zones 10 and 15
zones 4 and 5	zones 1 and 11	zones 4 and 13	zones 13 and 15
zones 1 and 8	zones 8 and 11	zones 5 and 13	zones 12 and 17
zones 6 and 8	zones 2 and 12	zones 1 and 14	zones 16 and 19
zones 2 and 9	zones 9 and 12	zones 11 and 14	

Table 2. Results from cross-correlation

Close examination of Table 2 leads to the following conclusions: Some zones because of their high seismicity level seem to be correlated to almost every other zone e.g. zone 2. Although significance tests are possible (Solow, 1995) they have no practical use. The existence of zero values affects the reliability of the results and makes necessary the use of a more elaborated method.

4. Stochastic Point Process

4.1 Method

Stochastic point process have been applied many times in the past (Vere-Jones, 1970) in order to describe a seismic sequence of occurrence times. In such models, the intensity function, by which the point process is defined, gives the number of shocks per unit time.

For the investigation of the causal relation between two seismic zones, the following model has been used (Ogata, *et al*, 1982, De Natale, *et al*, 1988):

$$\lambda(t) = \mu + \sum_{t_i < t} g(t - t_i) + \sum_{r_j < t} h(t - r_j) \quad (2)$$

In this model two sets of earthquakes are involved. The first one (output series) occur at times t_i and the second (input series) at times r_j . In (2) μ is the Poisson rate, $g(t)$ is the rate due to the self-exiting effect and it refers only to the shocks of the output series and $h(t)$ is the rate due to the effect of the external (input) sequence. If $h(t)=0$, there is no relation between the two zones. If $g(t)=0$, the output process is a double Poisson stochastic process whose intensity is modulated only by the input series. If $h(t)=g(t)=0$, the process is Poissonian with rate μ . Laguerre-type polynomials have been used for modelling $h(t)$ and $g(t)$

$$g(t) = \sum_{k=1}^K \alpha_k t^{k-1} e^{-\alpha} \quad \alpha_0 = 0 \quad h(t) = \sum_{l=1}^L \tilde{\alpha}_l t^{l-1} e^{-\alpha} \quad \beta_0 = 0$$

For the selection of the orders K and L of the Laguerre polynomials, Akaike's Information Criterion has been employed. According to it, $AIC = (-2) \max(\loglikelihood) + 2(d)$, where $d = K + L + 1$ (the number of parameters). c was given several fixed values in different runs of the program.. Parameters have been estimated by applying the method of Maximum Likelihood and they were kept non negative in order to avoid meaningless values for $h(t)$ and $g(t)$.

4.2 Application and Results

The time unit used was the month with the origin 0 corresponding to January 1901. All data were transformed into months of occurrence and the time interval covered the period [0 , 1044]. It was clear from the very beginning that the choice of the magnitude of the

threshold would seriously affect the number of parameters involved, that is K and L. In particular, the higher the threshold the less related the earthquakes within a zone and the less data available. A threshold of $M > 5$ proved to be a good compromise. The parameter c has been tested for every value in the interval 0 to 5 with step 0.05. All pairs of zones that showed a significant dependence $h(t) \neq 0$ along with the corresponding time of maximum probability of occurrence are listed below.

COMBINATIONS	MAXTIME	COMBINATIONS	MAXTIME
1 OVER 2	1	11 OVER 8	1
2 OVER 3	20	11 OVER 16	1
6 OVER 4	1	11 OVER 19	1
6 OVER 5	1	14 OVER 4	1
6 OVER 17	1	14 OVER 5	1
9 OVER 5	10	14 OVER 13	1
3 OVER 5	3	14 OVER 16	1
3 OVER 7	1	15 OVER 14	1
3 OVER 10	1	16 OVER 3	1
3 OVER 14	1	16 OVER 4	20
8 OVER 10	1	16 OVER 8	1
8 OVER 11	1	19 OVER 8	1
8 OVER 14	1	19 OVER 11	1
8 OVER 16	1	19 OVER 12	2
8 OVER 19	1	19 OVER 13	1
7 OVER 4	1	10 OVER 3	20
5 OVER 4	1	10 OVER 9	1
5 OVER 7	1	10 OVER 12	1
4 OVER 1	1	10 OVER 16	1
4 OVER 3	1	12 OVER 1	1
4 OVER 12	1	12 OVER 19	1
4 OVER 13	1	13 OVER 5	1
4 OVER 14	2		

Table 3. Results from Poisson Point Process.

Looking at table 3 and figure 1, the following observations can be made:

The length of time with the maximum probability of occurrence is in most cases 1 month which seems to be normal considering the short distance between zones. Causal relations exist along the Hellenic arc, in the Western part from North to South, parallel to the North Anatolian fault, and parallel to the subduction of the African plate mainly in the centre and East Aegean sea. All these findings agree with the tectonics of the Aegean area discussed in section 1. Results from the two methods employed do not always coincide. However, the

difficulties in the application of cross-correlation techniques, as previously presented make these techniques less reliable than the stochastic point process modeling.

5. Conclusion

Cross-correlation techniques and stochastic point process theory have been applied to model the relation between the 19 zones of the Aegean and the surrounding areas. The results, especially of the later, are generally in agreement with the tectonics of the Aegean which explain the seismic activity of this region.

References

- Chatfield, C. (1989). *The analysis of time series*. 4th edition, Chapman and Hall, London.
- De Natale, G., Musmeci, F. and Zollo, A. (1988). A Linear Intensity Model to Investigate the Causal Relation between Calabrian and North-Aegean Earthquake Sequences. *Geophysical Journal*, **95**, 285-293
- Hatzidimitriou, P. M., Papaxachos, B. C. and Karakaisis, G. F. (1994). Quantitative Seismicity of the Aegean and the Surrounding Area. *XXIV Gen. Ass. E. Sc. Athens* 19-24 Sept. 1994
- Makropoulos, K. C. and Burton, P.W. (1981). A Catalogue of Seismicity in Greece and the Adjacent Areas. *Geophys. J. R. Astr. Soc.* **65**, 741-762.
- Makropoulos, K. C., Drakopoulos, J. K. and Latousakis, J. B. (1989). A revised and extended earthquake catalogue for Greece since 1900. *Geophys. J. Int.* **98**, 391-394.
- Ogata, Y., Akaike, H. and Katsura, K. (1982). The application of Linear Intensity Models to the Investigation of Causal Relations between a Point Process and another Stochastic Process. *Ann. Inst. Math.*, **34**, Part B, 373-387.
- Papadopoulos, G. A., Kondopoulou, D. P., Leventakis, G. A. and Pavlides, S. B. (1986). Seismotectonics of the Aegean Region. *Tectonophysics*, **124** 67-84.
- Papazachos, B. C. (1990). Seismicity of the Aegean and Surrounding Area. *Tectonophysics*, **178** 287-308.
- Papazachos, B. C. and Papaioannou, C. A. (1993). Long-term Earthquake Prediction in the Aegean Area Based on a Time and Magnitude Predictable Model. *PAGEOPH* **140** No 4, 593-612
- Skordas, E., Meyer, K., Olsson, R. and Kulhanek, O. (1991). Causality between Interplate (North Atlantic) and Intraplate (Fennoscandia) Seismicities. *Tectonophysics*, **185**, 295-307.
- Solow, A. R. (1995). Identifying Regional Seismic Relationships by Cross-correlation. *PAGEOPH*, **144**, No 2, 301-306.
- Vere-Jones, D. (1995). Forecasting Earthquakes and Earthquake Risk. *International Journal of Forecasting*, **11**, 503-538.
- Vere-Jones, D. (1970). Stochastic Models for Earthquake Occurrence. *J. R. Stat. Soc.*, **32**, 1-45.