1e SÉRIE. T. XXXVIII. FASC. B. 2000

ISSN:1105-0004

ANNALES GÉOLOGIQUES DES PAYS HELLÉNIQUES

Fondées
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À la mémoire du Professeur J. DRAKOPOULOS

PREMIÈRE SÉRIE

TOME TRENT - HUITIÈME
FASC. B

ATHÈNES
DÈPARTMENT DE GÉOLOGIE
Panepistimiopolis. Athènes (157 84)
2000

A PROCEDURE TO ASSESS THE EVOLUTION OF A SEISMIC SEQUENCE

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I. INTRODUCTION

A systematic study of the seismic sequences in the area of Greece has started more than three decades ago (Papazachos et al., 1967; Drakopoulos, 1968) and this work continued with the detailed studies of foreshock and aftershock sequences. These studies led to interesting results concerning the earthquake prediction. It has been shown, for example, that 42% of the strong shallow earthquakes ($M \geq 6.0$) in Greece are preceded by one or more foreshocks with $M \geq 4.4$ (Papazachos, 1975), that the mean difference between the magnitude of the largest aftershock and of the mainshock of a sequence is 1.1 and that the probability for the generation of the largest aftershock during the first day after the generation of the mainshock is 53% (Papazachos, 1974a,b).

This research work led also to the identification of several categories of seismic sequences. The most common category includes the sequences which are composed of a mainshock and its aftershocks. A less frequent category is that when a strong earthquake is followed by smaller shocks up to the generation of a new strong earthquake which is followed by aftershocks. Rare is also the case when a strong earthquake is preceded by a large number of foreshocks. There are also cases when a seismic sequence is formed only by small earthquakes (swarms).

Interesting results have been derived by this research in relation to the time distribution (Papazachos, 1974a,b; Papazachos et al., 1982), spatial distribution (Scordilis et al., 1985; Papazachos et al., 1988), time-space distribution (Karakaisis, et al., 1985) and magnitude distribution (Papazachos, 1974a, 1975) of the seismic sequences.

A procedure is proposed in the present paper for estimating (predicting) the strongest earthquakes of a seismic sequence on the basis of the published knowledge and new experience on the time, space, time-space and magnitude of the non strong earthquakes of the sequence.

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II. TIME VARIATION OF THE FREQUENCY OF SHOCKS OF A SEISMIC SEQUENCE

The first category of seismic sequences which is mentioned above, that is, the generation of a mainshock which is followed by its aftershocks, is the usually observed category of seismic sequences of shallow mainshocks. For this reason the physical procedure of generation of such a seismic sequence is usually called **normal evolution** of this seismic sequence.

The frequency, n, of aftershocks (e.g daily number of shocks) of a normally evolving seismic sequence varies with time, according to the relation:

$$n = n_o t^{-h} \tag{1}$$

where t is the time (usually in days) measured from the origin time of the mainshock, n_o and h are parameters which are calculated by the available data (Mogi, 1962). A representative value for the earthquakes of the area of Greece is $h = 1.13$ (Papazachos, 1974b).

Relation (1) can be written in the linear form:

$$\log n = n_1 - h \log t \tag{2}$$

Thus, the parameters n_1(=$\log n_o$) and h can be calculated by the least squares method.

In the computer program used in the presend study, the mainshock origin time is considered as $t_o=0.0$, while the time axis in Fig. (1) is divided into logarithmic intervals with limits which are determined by the relation: $\log t^*_i = 0.1\ i$, $i =,,,-2,-1,0,1,2,,,,$. The duration, Δt^*_i of each interval is $\Delta t^*_i = t^*_{i+1} - t^*_i$. If N_i is the number of aftershocks in the time interval Δt^*_i, then the quantity $n_i = N_i / \Delta t^*_i$ shows the frequency of the aftershocks per time unit and is plotted against the middle of Δt^*_i.

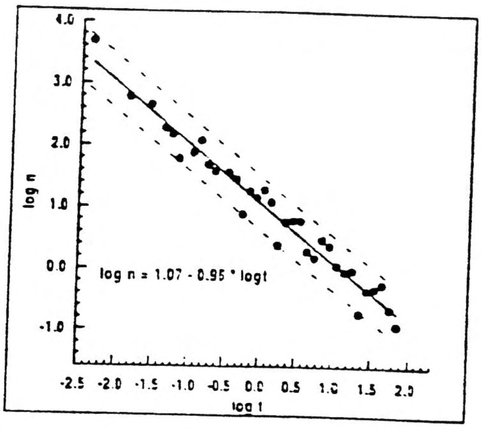

Fig.1. Time variation of the daily number of aftershocks (M≥3.5) of the Athens earthquake (7.9.1999, M≥5.9) as it has been determined by the computer program SSP.

Figure (1) shows the variation of the logarithm of the daily number of aftershocks of the Athens earthquake (7.9.1999, M=5.9) as a function of the logarithm of time (in days) according to relation (2). In the same figure a solid line, based on least squares and the dashed lines which define the 95% confidence intervals have been drawn. It is observed that almost all points are within the confidence intervals and for this reason the time variation of the frequency of shocks of this sequence is considered as normal.

Figure (2) shows the variation of the logarithm of the daily number of aftershocks of the largest foreshock (11.8.1953, M=6.8) and of the mainshock of Cephalonia (12.8.1953, M=7.2) as a function of the logarith of time (measured in days from the origin time of the largest foreshock).

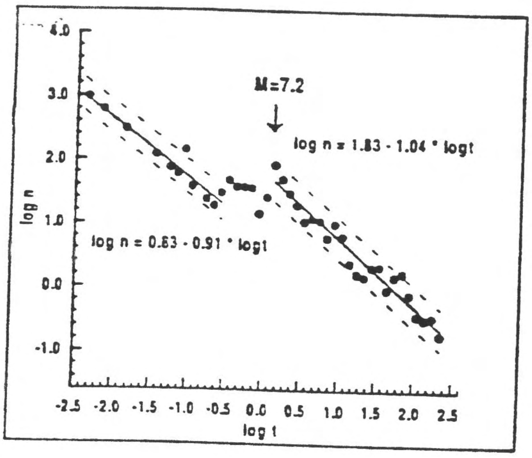

Fig.2. Time variation of the daily number of shocks for the seismic sequence of the Cephalonia earthquake (12.8.1953, M=7.2) as it has been determined by the computer program SSP.

It is observed that the time variation of the frequency of shocks which follow the 11.8.1953 earthquake (largest foreshock with M=6.8) is normal (within the 95% confidence intervals) up to some time when its behavior changes until the generation of the mainshock (12.8.1953). After that, the seismic sequence has again a normal behavior due to the generation of the aftershocks of the mainshock.

III. SPATIAL DISTRIBUTION OF THE SHOCKS OF A SEISMIC SEQUENCE

The spatial distribution of the foci of the shocks of a seismic sequence gives useful information for the kind of this sequence. Thus, the spatial distribution of aftershocks of a mainshock defines the rupture (fault) zone of the mainshocks, while foreshocks are usually located near the focus of the mainshock (Papazachos et al., 1983).

Figure (3) shows the geographical distribution of foreshocks (black circles), of aftershocks (grey circles) and of the epicenter of the mainshock (star) which occurred in the area of Kozani (13.5.1995, M=6.6). It is observed that the epicenters of the foreshocks are close to the epicenter of the mainshock while the epicenters of aftershocks cover the whole fault zone.

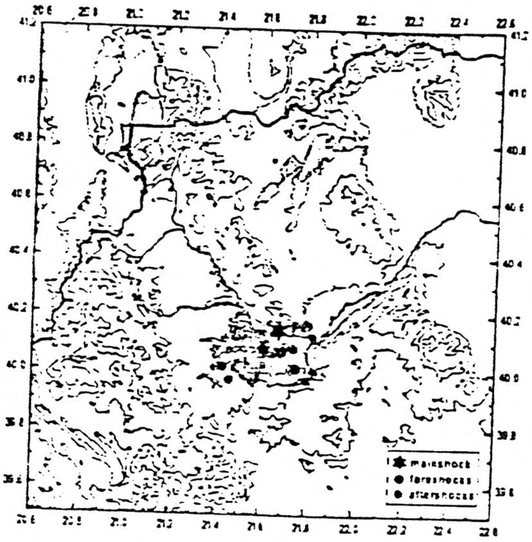

Fig.3. Geographical distribution of the epicenters of foreshocks, aftershocks and of the mainshock which occurred in the area of Kozani (13.5.1995, M=6.6) as it has been determined by the computer program SSP.

Figure (4) shows the projections on a vertical plane parallel (upper part) and normal (lower part) to the faul strike, of the foci of foreshocks (black circles), of aftershocks (grey circles) and of the mainshock (star) which occurred in the area of Kozani (13.5.1995, M=6.6). These plots give a clear picture about the distribution in space of the shocks of this sequence.

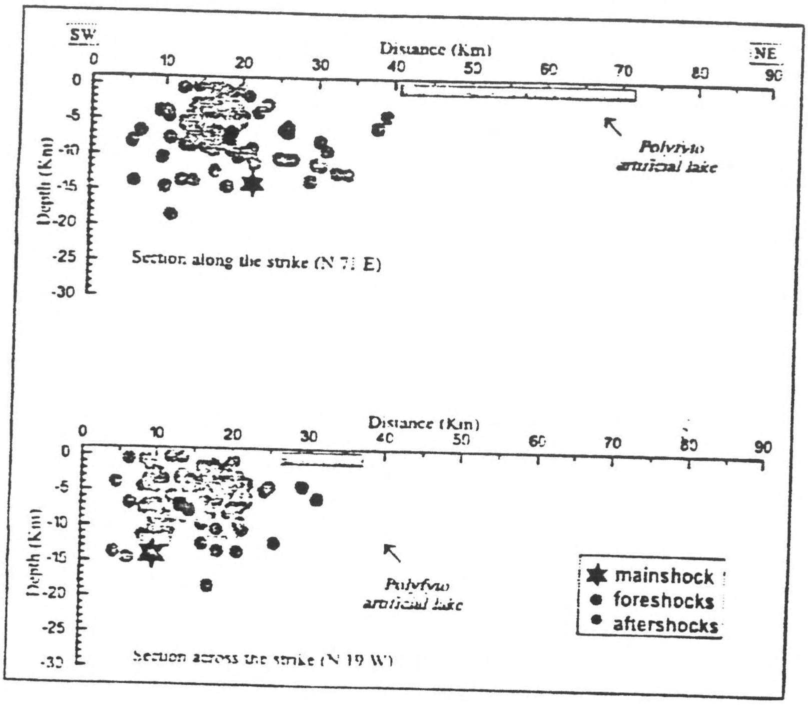

Fig.4. Spatial distribution of the shocks of the seismic sequence of the Kozani earthquake (13.5.1995, M=6.6) as it has been determined by the computer program SSP. The upper and lower part show projections of the foci on a vertical plane parallel to the fault strike and normal to the fault strike, respectivelly.

IV. SPACE - TIME DISTRIBUTION OF THE SHOCKS OF A SEISMIC SEQUENCE

The study of the space - time distribution of the shocks of a seismic sequence is of importance because it gives a more general idea on its behavior. One of the most important results of this research is the fact that immediately after the generation of a mainshock near the middle of a seismic fault, the seismic activity migrates mainly to the one end of the fault where the largest aftershocks occur later. When the mainshock is generated near the one end of the fault the seismic activity migrates to its other end where the largest aftershocks occur later (Karakaisis et al., 1985; Scordilis et al., 1985).

Figure (5) shows the distribution of the projection of the foci of aftershocks of the Alkionides earthquake (23.2.1981, M=6.7) on the strike of the seismic fault as a function of time. It is observed that, immediately after the generation of the mainshock in the western part of the fault, the aftershock activity migrated to its eastern part where the destructive earthquake (the second largest aftershock) occurred on March 4 (M=6.3).

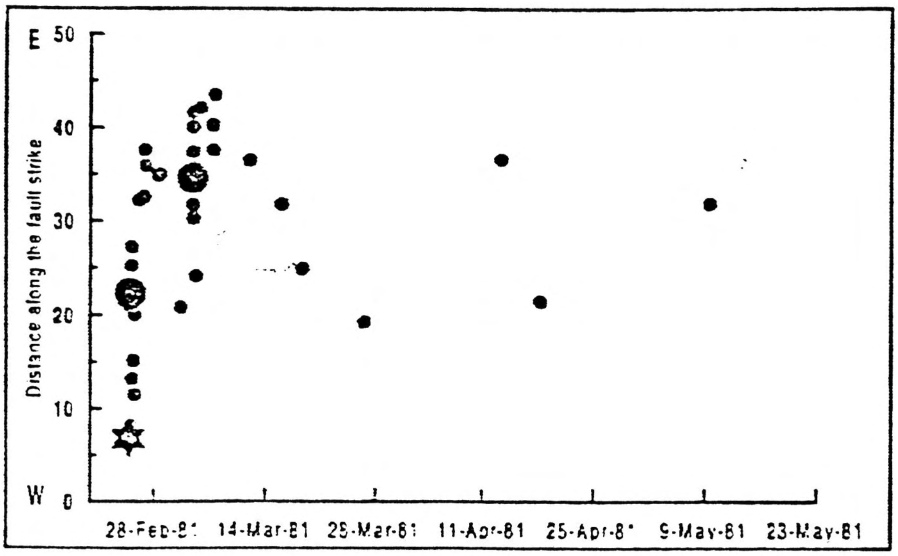

Fig.5. Space - time distribution of the aftershocks of the Alkionides earthquake (23.2.1981, M=6.7) as it has been determined by the computer program SSP.

V. MAGNITUDE DISTRIBUTION OF THE SHOCKS OF A SEISMIC SEQUENCE

It is known that the magnitude distribution of earthquakes is described by the Gutenberg and Richter (1944) relation:

$$\log N = a - bM \qquad (3)$$

where N is the number of earthquakes with magnitude equal to and larger than M, and a, b are parameters which are determined by the observations. This relation holds also for the seismic sequences. In this case the value of the parameter b characterizes the kind of the seismic sequence because this value is relatively small (~0.7) for foreshock sequences, relativelly large (~1.0) for aftershock sequences and even larger for swarms of earthquakes (Papazachos, 1974a).

Figure (6) shows the time variation of the mean magnitude, $\overline{M}$ (for M_{min}=3.5), and of the parameter b as this parameter was calculated by the relation (3) for the aftershocks of the

Athens earthquake (7.9.1999, M=5.9). It is observed that these parameters remain almost constant (independent of time) which means a normal behavior of this seismic sequence. It is also observed that the standard deviation of the mean magnitude remains also constant (±0.4), as well as the standard deviation of b (±0.05).

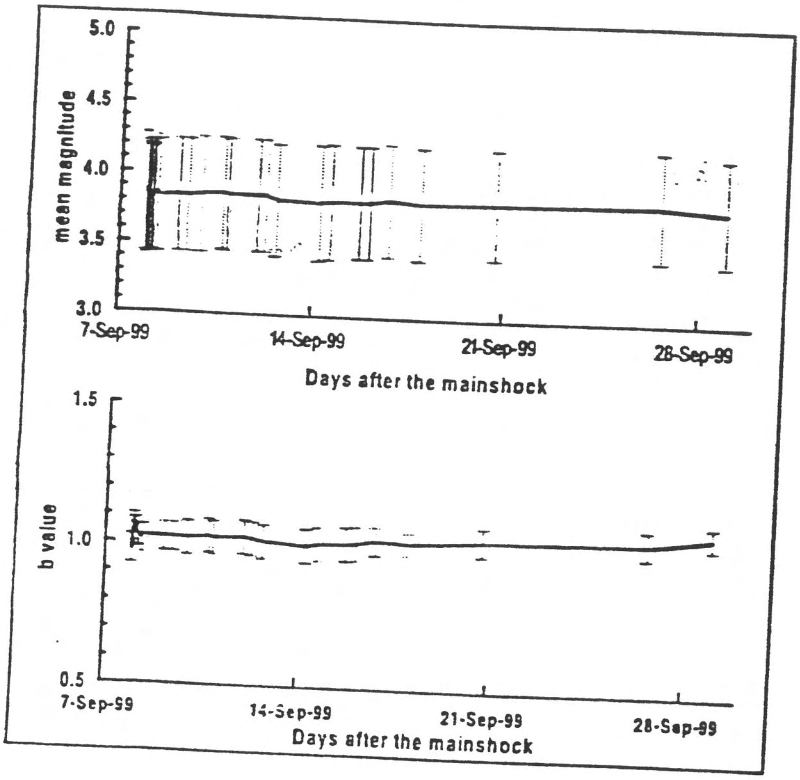

Fig.6. Time variation of the mean magnitude (upper part) and of the parameter b (lower part) for the aftershocks of the Athens earthquake (7.9.1999, M=5.9), as it has been determined by the computer program SSP. The error bars show the standard deviation.

VI. HOW THE METHODOLOGY IS APPLIED

The estimation of the evolution of the seismic activity in an area during a period of seismic excitation is a problem of great social importance because it can lead to preparedness measures for the protection of people.

The procedure for such an estimation must start immediately after the beginning of the seismic excitation (within a time of less than one hour) by taking the proper measurements on the seismograms, interpreting the data and calculating first values of the parameters which define the time, space and magnitude distribution of the shocks. This procedure must be repeated in time intervals which depend on the characteristics of the seismic sequence (from some hours to some days).

The observational data which are used for such studies usually come from three sources.

The first source is a **permanent network** of seismographs which is in continuous operation (the National Network of Stations, the network of the University of Thessaloniki, etc). With such a network a determination with a fairly good accuracy can be made of the origin time of the shocks (±2sec), of the epicenters and focal depths (~10km) and of the magnitudes (±0.3) of the strong earthquakes (M≥4.0). These data are usually the only information which is available at the beginning of the seismic excitation for making this study.

The second source of observational data for such studies is a **portable network** of seismographs which has already been installed in the epicentral area or will be installed as soon as possible after the beginning of the seismic excitation. With such a dense network of portable stations we can determine very accurately the origin times (±0.3sec), the epicenters (~1km) and the focal depths (~2km) of the very small earthquakes too.

The third source of observational data are the records of the **accelerometers** which are already installed in the epicentral area or are installed there immediately after the beginning of the seismic excitation. The use of accelerograms contribute to the increase of the accuracy in the location of the focus and of the origin time of the relatively large shocks (M≥4.0) because we can measure accurately (~0.2sec) the time difference between the arrivals of the longitudinal and shear waves at the site where the accelerograph is installed and use this difference in the determination of the earthquake parameters (origin time, epicenter, focal depth).

It must be emphasized that the effective application of this methodology by the use of the computer program SEISMIC SEQUENCE PREDICTION requires a representative sample of data. As it comes out from our experience, for an accurate calculation of each one of the above mentioned parameters (b, $\overline{M}$), a sample of observations of about 40 shocks (aftershocks, etc) is required. In the above given examples (Fig. 6) each parameter was calculated by 40 observations (40 shocks).

ABSTRACT

A procedure (methodology) is developed by which it is possible to assess (predict) the way a seismic sequence is evolved. This procedure is based on the study of the time, space, time-space and magnitude distribution of non strong earthquakes of a seismic sequence and has as a goal the assessment (prediction) of the strong earthquakes of the sequence. It is possible to

test, by this methodology, if a seismic sequence is normally evolved, that is, if the sequence is a normal aftershock sequence, when we expect the generation of only much smaller earthquakes (aftershocks) than the mainshock which has already occurred or if a seismic sequence is not normally evolved, when we expect an earthquake of the same order or even larger than those which have already occurred. Even in the case of a normally evolved aftershock sequence the methodology can be applied to locate accurately the larger aftershocks which some times cause considerable damage or even collapses of the already suffered structures. For this purpose, a computer program, called SEISMIC SEQUENCE PREDICTION (SSP) has been developed.

ΠΕΡΙΛΗΨΗ

Περιγράφεται διαδικασία (μεθοδολογία) με την οποία μπορεί να ελεγχθεί ο τρόπος εξέλιξης μιας σεισμικής ακολουθίας. Η διαδικασία βασίζεται στη μελέτη της χρονικής, χωρικής, χωροχρονικής και κατά μέγεθος κατανομής των μη πολύ ισχυρών σεισμών μιας σεισμικής ακολουθίας και στοχεύει στην προεκτίμηση (πρόγνωση) των ισχυρών σεισμών της ακολουθίας. Με τη διαδικασία αυτή μπορεί να ελεγχθεί αν η ακολουθία εξελίσσεται ομαλά, αν δηλαδή πρόκειται για κανονική μετασεισμική ακολουθία, οπότε δεν αναμένουμε τη γένεση άλλου σεισμού αναλόγου ή και μεγαλύτερου μεγέθους από τον κύριο σεισμό που ήδη έγινε, ή αν η ακολουθία δεν εξελίσσεται ομαλά, οπότε αναμένεται σεισμός αναλόγου ή και μεγαλύτερου μεγέθους από όλους τους σεισμούς που ήδη έγιναν. Ακόμα και στην περίπτωση ομαλής εξέλιξης μιάς μετασεισμικής ακολουθίας η μέθοδος παρέχει τη δυνατότητα εντοπισμού των εστιών των μεγαλύτερων μετασεισμών οι οποίοι πολλές φορές προκαλούν σημαντικές πρόσθετες βλάβες στα ήδη καταπονημένα από τον κύριο σεισμό κτίρια ή και καταρρεύσεις τέτοιων κτιρίων. Για το λόγο αυτό γράφτηκε ένα πρόγραμμα ηλεκτρονικού υπολογιστή το οποίο ονομάζεται SEISMIC SEQUENCE PREDICTION (SSP).

Acknowledgements

Part of this work was financed by the District of Central Macedonia, Greece (Project 7454 of the Research Committee of the Aristotle University of Thessaloniki) and the Ministry of Education of Greece.

REFERENCES

Gutenberg, B. and Richter, C.F. Frequency of earthquakes in California. "Bull. Seism. Soc. Am.", 34, 185-188, 1944.

Drakopoulos, J.K. Characteristic parameters of fore and after-seismic sequences in the area of Greece. "Ph. D. Thesis, University of Athens", 1-128, 1968.

Karakaisis, G.F., Karakostas, B.G., Papadimitriou, E.E., Scordilis, E.M. and Papazachos, B.C. Seismic sequences in Greece interpreted in terms of the barrier model. "Nature", 315, 212-214, 1985.

Mogi. K. On the time distribution of aftershocks accompanying the recent major earthquakes in and near Japan. "Bull. Earthq. Res. Inst.", 40, 107-124, 1962.

Papazachos, B.C. On certain aftershock and foreshock parameters in the area of Greece. "Annali di Geofisica", 27, 497-515, 1974a.

Papazachos, B.C. On the time distribution of aftershocks and foreshocks in the area of Greece. "Pure and Applied Geophysics", 112, 627-631, 1974b.

Papazachos, B.C. Foreshocks and earthquake prediction. "Tectonophysics", 28, 213-226, 1975.

Papazachos, B.C., Delibasis, N., Liapis, N., Moumoulidis, G. and Purcaru, G. Aftershock sequences of some large earthquakes in the region of Greece. "Annali di Geofisica", 20, 1-93, 1967.

Papazachos, B.C., Tsapanos, T.M. and Panagiotopoulos, D.G. A premonitory pattern of earthquakes in northern Greece. "Nature", 296, 232-235, 1982.

Papazachos, B.C., Panagiotopoulos, D. G., Tsapanos, T. M., Mountrakis, D. M. and Dimopoulos, G. Ch. A study of the summer seismic sequence in the Magnesia region of central Greece. "Geophys. J. R. astr. Soc.", 75, 155-168, 1983.

Papazachos, B.C., Kiratzi, A., Karakostas, B., Panagiotopoulos, D., Scordilis, E., and Mountrakis, D.M. Surface fault traces, fault plane solution and spatial distribution of aftershocks of the September 13, 1986 earthquake of Kalamata (southern Greece). "Pure and Applied Geophysics", 126, 55-68, 1988.

Scordilis, E.M., Karakaisis, G.F., Karacostas, B.G., Panagiotopoulos, D.G., Comninakis, P.E. and Papazachos, B.C. Evidence for transform faulting in the Ionian Sea. The Cephalonia island earthquake sequence of 1983. "Pure and Applied Geophysics", 123, 388-397, 1985.