

LONG TERM EARTHQUAKE PREDICTION IN VRANCEA
REGION, ROMANIA, BASED ON A TIME PREDICTABLE MODEL

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A B S T R A C T

On the basis of instrumental and historical information on strong intermediate-depth main shocks which occurred in the Vrancea region of the Romanian territory, four repeat times (five main shocks) have been determined. By using these repeat times, the following relation was obtained:

$$\log T_t = 0.10M_{\min} + 0.31M_p + a$$

where T is the repeat time, measured in years, M_p is the magnitude of the preceding main shock, M_{\min} is the magnitude of the smallest earthquake considered and "a" is a constant which corresponds to the source and equals to -1.45.

On the basis of this relation the probability of occurrence of a new strong earthquake in Vrancea region during the next decades has been calculated. It was found that this probability, for the occurrence of a main shock with magnitude $M_s \geq 7.0$, is less than 0.40 for the next two decades and more than 0.70 for the next three decades or so.

ΜΑΚΡΟΠΡΟΘΕΣΜΗ ΠΡΟΓΝΩΣΗ ΣΕΙΣΜΩΝ ΣΤΗΝ ΠΕΡΙΟΧΗ VRANCEA
ΤΗΣ ΡΟΥΜΑΝΙΑΣ ΒΑΣΙΣΜΕΝΗ ΣΤΟ ΜΟΝΤΕΛΟ ΠΡΟΓΝΩΣΗΣ ΤΟΥ ΧΡΟΝΟΥ
ΤΩΝ ΙΣΧΥΡΩΝ ΣΕΙΣΜΩΝ

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Π Ε Ρ Ι Λ Η Ψ Η

Ιστορικά και ενόργανα δεδομένα ισχυρών ενδιαμέσου βάθους σεισμών στην περιοχή Vrancea της Ρουμανίας χρησιμοποιήθηκαν για ναδειχθεί ότι ο χρόνος T_t (σε έτη) μεταξύ δύο ισχυρών σεισμών δίνεται από τη σχέση:

$$\text{Log} T_t = 0.10M_{\min} + 0.31M_p + a$$

όπου M_{\min} είναι το επιφανειακό μέγεθος του μικρότερου κύριου σεισμού που θεωρούμε, M_p το μέγεθος του κύριου σεισμού που προηγήθηκε και "a" μια σταθερά που αντιστοιχεί στη πηγή και υπολογίσθηκε ίση με -1.45.

Με βάση τη σχέση αυτή υπολογίστηκε ότι η πιθανότητα για τη γένεση ενός κύριου σεισμού με μέγεθος $M_s \geq 7.0$ είναι μικρότερη του 0.40 για τις δύο επόμενες δεκαετίες (1993-2012) και μεγαλύτερη του 0.70 για τις επόμενες τρεις δεκαετίες (1993-2022).

INTRODUCTION

With the purpose to estimate the long term probabilities for the generation of strong earthquakes on single faults, the time dependent model seems to be more plausible in comparison to the slip predictable model (Wesnousky et al., 1984; Astiz and Kanamori, 1984; Nishenko and Buland, 1987). This model holds even if the seismic source includes, in addition to the main fault where the characteristic earthquake is generated, other smaller faults where smaller shocks also occur (Papazachos, 1989).

According to the time-predictable model, the time of occurrence of a future earthquake in a certain seismic source depends on the size and the time of occurrence of the last earthquake in the source. On the other hand, according to the slip-predictable model, the size of a future earthquake depends on the time elapsed since the last earthquake. It means that we can predict, in principle, the size of a future earthquake by the slip-predictable model and the time of its occurrence by the time-predictable model (Bufe et al., 1977, Shimazaki and Nakata, 1980).

Very recently, Papazachos (1988a,b; 1992) concluded that the time-predictable model holds for the shallow earthquakes in Greece and he proposed a relation of the form:

$$\log T = bM_{\min} + cM_p + a \quad (1)$$

between the repeat time, T , the magnitude, M_p , of the preceding main shock and the magnitude, M_{\min} , of the smallest main shock considered in a certain seismogenic source. A strong positive correlation between $\log T$ and M_p and a weak negative correlation between $\log T$ and M_f , where M_f is the magnitude of the following main shock, has been found. In addition, he proposed another relation between M_p and M_f , which in combination with equation (1) leads to a model that permits an estimation of the time and magnitude of the expected main shock in a certain seismogenic source.

In the present study, we try to test the effectiveness of the time predictable model at the seismogenic source of Vrancea region in Romania with data from intermediate depth earthquakes and to determine the probabilities for the occurrence of strong earthquakes for the next years in this region.

SEISMOTECTONICS AND PREVIOUS WORK ON EARTHQUAKE PREDICTION IN VRANCEA

The Vrancea seismogenic area is located near the Romanian Carpathian Arc Bend (between the parallels of 45.3°N and 46.0°N and between the meridians of 26.0°E and 27.0°E). The intermediate depth earthquake generating stress system and the subduction process under the Eastern Carpathians have been described by various researchers (Radu and Purcaru, 1964; Roman, 1970, 1973; Constantinescu, 1978; Morelli et al., 1975; Purcaru, 1979; Marza, 1982; Oncescu, 1984;). This system occupies an area between the Eastern European major plate, the Moesian minor plate and

Transylvania which behaves as an intra-Alpine minor plate.

Most of the observed seismic activity is in the depth of 80-150 km (the maximum depth is about 200 km). The strongest intermediate depth earthquakes have magnitudes $M_s \sim 7.5$. The seismic activity at normal depth is much less significant than the main activity from intermediate depths but seems to be connected with the intermediate depth activity. On the other hand, there is no volcanic activity in the present day in this region. The Vrancea region is isolated from Alpine-Himalayan seismic belt and the aforementioned characteristics make it difficult to explain the cause of the intermediate depth earthquakes in terms of a typical subduction in a collision process. Apostol et al. (1985) suggested that the Vrancea region is a post-subduction area in the present time with a dead slab. Their model suggested a compression in Lower Miocene with subduction of oceanic crust and consumption of the oceanic crust in Neogene with associated volcanism.

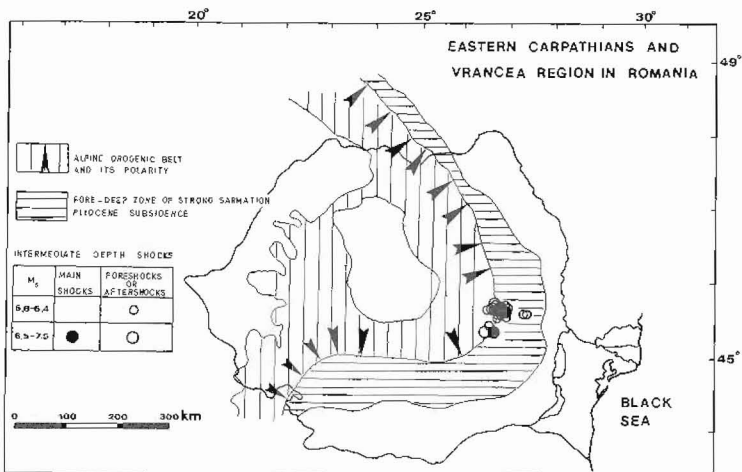


Fig.1. The seismogenic source of Vrancea region in Romania with the epicenters of intermediate depth earthquakes and basic geological information (modified from Morelli et al., 1975).

Taking into account the characteristics of Vrancea seismic region several researchers tried to apply some ideas to predict the seismic activity. Purcaru (1974,1979) attempted to describe the recurrence of intermediate depth earthquakes in Vrancea by a superposition of quasi-cycles. On the other hand, the investigation of seismicity revealed several precursors: seismic gaps, changes of seismicity rates, b-value fluctuations etc., which all together prove that quiescence patterns work very well for the Romanian intermediate depth earthquakes (Apostol et al., 1985). Several other methods (temporal variation of focal mechanism, asperity distribution and application of the percolation theory to earthquakes, investigations on the energy release etc.) have been applied by other researchers (Radu et

al., 1984; Radu and Oncescu, 1985; Trifu and Radulian, 1989; Ardeleanu and Popescu, 1990; Ardeleanu and Smalbergher, 1990; Marza, 1991; Trifu and Radulian, 1991; Radulian and Trifu, 1991) to investigate premonitory seismicity in Vrancea region.

DATA AND METHOD

The foci of intermediate depth earthquakes in Vrancea region form a well-defined seismic volume situated beneath the Carpathian arc in Romania territory, dipping down to 200 km depth (Oncescu, 1984; Trifu and Radulian, 1989; Trifu, 1990). This seismogenic source is shown in fig.(1) along with the epicenters of the complete data of the intermediate depth earthquakes which are used in this study and some basic geological information modified from Morelli et al., (1975). Black circles show epicentres of the main shocks. Open circles show epicentres of the foreshocks and aftershocks in the broad sense, that is, earthquakes which may occur up to several years before or after the main shock, respectively. We use the terms "aftershock" and "foreshock" in their broad sense because we want a model which can predict the main shocks in the seismogenic source of Vrancea, that is, the strong earthquakes which occur at the beginning and the end of each seismic cycle and not smaller earthquakes which occur during the preseismic and postseismic activations. In particular, as foreshocks and aftershocks have been considered the earthquakes which had preceded or followed the main shocks with magnitudes 5.5-5.7, 5.8-6.0, 6.1-7.0 and larger than 7.0, up to 6,7,9 and 13.5 years, respectively (Papazachos, 1992).

Information on the surface wave magnitudes and on the epicentres of the earthquakes plotted in fig. (1) were received from the catalogues of Karnik, (1968, 1971) and Shebalin et al., (1974) for the period 1880-1904, of Comninakis and Papazachos, (1978) for the period 1908-1948 and from the monthly bulletins of the National Earthquake Information Center of Geological Survey of U.S. Department of the Interior for the period 1977-1990.

Information on main shocks used in the present study is given in Table (1). The first column of this table gives the name of the seismogenic source, while the second one gives the year since when the data are complete for a certain minimum magnitude, which is written next to it. It means that the data are complete for earthquakes with magnitudes $M_s \geq 6.5$ during 1880-1991 and for $M_s \geq 5.8$ during 1901-1991. This completeness has been determined on the basis of information given in the catalogues.

The third, fourth and fifth columns of table (1) give the date, epicentre (North latitude, East longitude) and the surface wave magnitude for the main shocks which satisfy the completeness condition which has written at the second column. The sixth column gives the cumulative magnitude, M , of each sequence, that is, the magnitude which corresponds to the total moment released by the major shocks (main shocks and large foreshocks and aftershocks) of each sequence according to a relation between surface wave magnitude and seismic moment (Kanamori, 1977). These cumulative magnitudes were used in the present study instead of the magnitudes of main shocks although the differences are small (Papazachos, 1992).

Table 1. Information on the basic data used for the seismogenic source

Source	Completeness	Date	Epicenter	M_s	M
ROMANIA	1880, 6.5	25:12: 1880	45.8 26.6	6.9	6.9
	1901, 5.8	17:08: 1893	45.8 26.6	6.6	6.6
		06:10: 1908	45.5 26.5	6.8	6.9
		10:11: 1940	45.8 26.7	7.4	7.5
		04:03: 1977	45.8 26.7	7.4	7.5

Table 2. Data used to determine the parameters of the empirical relations

Source	M_{min}	M_p	M_f	T	t_p	t_f
ROMANIA	6.6	6.9	6.6	12.64	1880	1893
	6.6	6.6	6.9	15.14	1893	1908
	6.6	6.9	7.5	32.09	1908	1940
	6.6	7.5	7.5	36.32	1940	1977
	6.9	6.9	6.9	27.78	1880	1908
	6.9	6.9	7.5	32.09	1908	1940
	6.9	7.5	7.5	36.32	1940	1977
	7.5	7.5	7.5	36.32	1940	1977

Table (2) gives information on the minimum magnitude, M_{min} , of the main shock, the magnitude of the preceding main shock, M_p , the magnitude of the following main shock, M_f , the interevent (repeat) time, T, between the two shocks, the year of occurrence of the preceding main shock, t_p , and the following one, t_f , as these values were derived from the basic data of Table 1. To understand the way in which these values were derived from Table 1 we will explain this procedure for this source. We start with the smallest main shock which occurred in 1893 and has magnitude $M_{min}=6.6$. The first repeat time ($T=12.64$ years), which holds for this minimum magnitude, is the interevent time between the earthquake which occurred on 25.12.1880 ($M_p=6.9$, $t_p=1880$) and the main shock which occurred on 17.08.1893 ($M_f=6.6$, $t_f=1893$) and is written in the first line of Table 2 with the corresponding values of M_{min} , M_p , M_f , t_p and t_f . The second repeat time ($T=15.14$

$t_p=1893$) and the main shock which occurred on 06.10.1908 ($M_p=6.9$, $t_p=1908$) and is written on the second line of Table 2. Considering the same M_{min} ($=6.6$) the values of the third and fourth lines of Table 2 have been determined by the same way.

In the next step we ignore the main shocks with $M \leq 6.6$. From table 1 it is derived that the smallest mainshock now is $M=6.9$. We follow the same procedure until the last M_{min} is considered.

DEPENDENCE OF THE REPEAT TIME ON THE MAGNITUDE OF THE MINIMUM AND THE PRECEDING MAIN SHOCKS

Papazachos (1992), considering about 240 interevent times from 49 seismogenic sources in Greece and surrounding area, found that the parameters b and c of the equation (1) are equal to 0.36 and 0.35, respectively. In the present study 8 interevent times were considered. By the use of the b and c mentioned values as initial ones and the information given in Table 2 an initial mean value, a, of the parameter a_i ($i=1,..,n$) was calculated by relation (1). After this, the relation (1) can be written as:

$$y = \log T_i - a = bM_{min} + cM_p \quad (2)$$

New values for the parameters b and c were calculated by applying least squares' differential correction on all the data of this source for the relation (2). By the use of the new values of b and c the procedure was repeated to calculate new values for the parameter, a, which in turn are used for the calculation of new values for b and c and so on, until convergence was achieved, that is, stable values for b, c and a. These final values are:

$$b=0.10 \quad c=0.31 \quad a=-1.46$$

with standard deviation $\sigma_y=0.13$ and multiple correlation coefficient $R=0.71$.

The larger value of the parameter "c" in respect to "b" implies that the dependence of the interevent time on the magnitude of the preceding main shock is stronger than the dependence of this time on the minimum magnitude. Moreover, the positive value of the parameter c($=0.31$) means that the time-predictable model is valid for the intermediate depth main shocks in Vrancea area.

LONG TERM EARTHQUAKE PREDICTION IN VRANCEA

Papazachos (1988b, 1991) has proposed that the lognormal distribution of the ratio T/T_c , where T are the observed interevent times between successive mainshocks in a certain seismogenic source and T_c is the corresponding theoretical value given by relation (1), provides a better fit than the Gaussian and Weibull distributions. Unlike normal distribution, where the probability of appearance of a parameter value is the same, independently of the value size, in the lognormal distribution

this probability is a function of neighbouring values of this parameter (Aitchinson and Brown, 1963). Figure (2) displays the frequency of $\log(T/T_t)$ and the theoretical normal distribution, which has a mean equal to zero and standard deviation equal to 0.13.

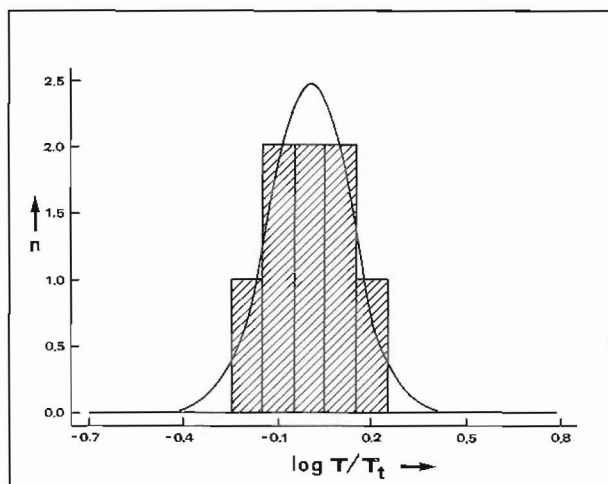


Fig.2. The frequency distribution of the observed repeat times to the theoretical one.

Assuming that the lognormal distribution holds for this seismogenic source and taking into account the time of occurrence and the magnitude of the last main shock, the probabilities of occurrence during the next 10,20,30,40,50 years for earthquakes with magnitudes equal to or larger than 7.0 were calculated. These probabilities are given on Table 3.

CONCLUSION

In the present study, the validity of the time-predictable model in the seismogenic source of Vrancea region in Romania is examined. It was found that the dependence of the repeat time, T , on the magnitude of the preceding main shock, M_p , is strong and positive ($c=0.31$). On the other hand the dependence of T , on the magnitude of the minimum main shock is weaker ($b=0.10$). This result supports the basic concept of the time-predictable model, that is, the larger the magnitude of the preceding mainshock, the longer the time interval till the next one.

Taking into account that the time-predictable model holds, the observed, T , and theoretical, T_t , repeat times were used for long-term earthquake prediction. Assuming that the lognormal distribution of the ratio T/T_t provides a good fit to the empirical data, the probabilities for the occurrence of strong ($M_s \geq 7.0$) intermediate depth earthquakes have been calculated, on the basis of this model, for the next 50 years in the seismogenic region of Vrancea.

Table 3. Probabilities, P, of occurrence during the next 10-50 years for mainshocks with $M_s \geq 7.0$ in Vrancea.

----- $M_s = 7.0$ -----	
T (years)	P

10	0.07
20	0.38
30	0.71
40	0.89
50	0.96

During the next 40 years, the probability estimated for the generation of an earthquake with $M_s \geq 7.0$ is very high ($P > 0.89$). This result is in agreement with the results found by a long term earthquake prediction in Vrancea region on intermediate depth earthquakes by Purcaru (1974, 1979), who predicted two strong intermediate depth earthquakes in 2030-2040 with magnitude $M_6.7-7.0$ and another one with maximum magnitude $M_{7.5-7.7}$ in 2070-2090.

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