LONG TERM EARTHQUAKE PREDICTION IN NORTH PACIFIC SEISMIC ZONE BASED ON THE TIME AND MAGNITUDE PREDICTABLE MODEL

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A B S T R A C T

Repeat times of the strong shallow mainshocks in 12 seismogenic sources along the North Pacific seismic zone have been estimated and used for the determination of the following relations:

$$logT_t=0.30M_{min}+0.15M_p-0.27\log\dot{M}_o+5.24$$

$$M_f=1.05M_{min}-0.47M_p+0.60\log\dot{M}_o-12.39$$

where T_t is the interevent time, measured in years, M_{min} the surface wave magnitude of the smallest mainshock considered, M_p the magnitude of the preceding mainshock, M_f the magnitude of the following mainshock, $\dot{M}_o$ the moment rate in each source per year. The probabilities for the occurrence and the magnitudes of the expected next large ($M_s\geq7.5$) shallow mainshocks in the twelve seismogenic sources during the next decade are determined, based on these two relations, and adopting a lognormal distribution for earthquake interevent times.

ΜΑΚΡΑΣ ΔΙΑΡΚΕΙΑΣ ΠΡΟΓΝΩΣΗ ΣΕΙΣΜΩΝ ΣΤΗ ΣΕΙΣΜΙΚΗ ΖΩΝΗ ΤΟΥ ΒΟΡΕΙΟΥ ΕΙΡΗΝΙΚΟΥ ΜΕ ΒΑΣΗ ΤΟ ΧΡΟΝΙΚΑ ΕΞΑΡΤΟΜΕΝΟ ΜΟΝΤΕΛΟ

Παπαδημητρίου, Ε.Ε.

Π Ε Ρ Ι Λ Η Ψ Η

Οι χρόνοι επανάληψης των ισχυρών επιφανειακών κύριων σεισμών σε 12 σεισμογόνες πηγές κατά μήκος της σεισμικής ζώνης του Βόρειου Ειρηνικού υπολογίστηκαν και χρησιμοποιήθηκαν για τον υπολογισμό των παρακάτω σχέσεων:

$$logT_t=0.30M_{min}+0.15M_p-0.27\log\dot{M}_o+5.24$$

$$M_f=1.05M_{min}-0.47M_p+0.60\log\dot{M}_o-12.39$$

όπου T_t είναι ο χρόνος επανάληψης σε έτη, M_{min} το επιφανειακό μέγεθος του μικρότερου κύριου σεισμού, M_p το μέγεθος του προηγούμενου κύριου σεισμού, M_f το μέγεθος του επόμενου κύριου σεισμού και $\dot{M}_o$ η ετήσια έκλυση της σεισμικής ροπής.

Υπολογίσθηκαν οι πιθανότητες γένεσης καθώς και το μέγεθος των αναμενόμενων ισχυρών ($M_s \geq 7.5$) επιφανειακών σεισμών σε κάθε μία από τις σεισμογόνες πηγές κατά την επόμενη δεκαετία, με βάση τις παραπάνω σχέσεις.

INTRODUCTION

Considerable progress has been made in the last few years by the scientists to find which model describes better the behaviour of large earthquakes interevent times. It has been shown by various investigators that the time-predictable model fits better the data coming from different regions of the world.

According to the time-predictable model, the time interval between large shocks depends on the size of the preceding event. This model is in accord with laboratory experiments on stick-slip behaviour on pre-existing faults (or surfaces) in that slip takes place in a given sample, when the stress reaches a level that is nearly constant among large events (Sykes, 1983).

Shimazaki and Nakata (1980) found at three locations in Japan that the time between successive great gap-filling earthquakes was proportional to the displacement in the first event. This "time-predictable" model suggests that great earthquakes recur when the strain released in the last event recovers. In principle, this allows the estimation of the time of the future occurrence of a given great earthquake.

Sykes and Quittmeyer (1981) found that the average repeat times of great earthquakes along simple plate boundaries of the world are governed by three factors: the relative velocity of the interacting plates, the ratio of seismic to aseismic motion and the geometry of the zone of plate contact, particularly the down-dip width. Furthermore, they found good support in the globally observed data on repeat times and displacements for the proposition that the time interval between large shocks at a given place is proportional to the displacement in the preceding earthquake rather than to the displacement in the shock that terminates that interval. Bufe et al. (1977) found such a relationship for small shocks along a segment of the Calaveras fault in California.

Papazachos (1988a,b, 1989, 1991, 1992, 1993) with the purpose to define time dependent relations between strong earthquakes which occurred in seismogenic sources in Greece, proposed a model where the interevent time, T_t, and the magnitude, M_f, of the following mainshock were quantitatively related to the magnitude, M_{min}, of the smallest considered mainshock and to the magnitude, M_p, of the preceding mainshock in each seismogenic source. This investigation resulted in proving that the time-predictable model fits better the data, and not the slip-predictable model. The methodology suggested by the above mentioned author has been improved recently (Papazachos and Papaioannou, 1993), to include a new term in the relations both for the interevent time and the magnitude of the expected mainshock. This term depends on the yearly moment rate in each seismogenic source. Based on this model they estimated the probability of occurrence and the magnitude of the expected strong shallow mainshocks in the seismogenic sources of the Aegean area.

The purpose of the present study is to apply the above mentioned methodology in the North Pacific seismic zone, that is, the Alaska-Aleutians-Kamchatka-Kuriles seismic zone. The Alaska-Aleutians island arc is one of the world's most active zones of earthquake activity, volcanism and subduction. Plate motion is largely strike slip off British Columbia to southern Alaska and occurs mainly by thrust faulting along the Aleutians. The Aleutian island arc marks the site of the subduction of the Pacific lithospheric plate under the North American lithospheric plate. The rupture zones, magnitudes and seismic moments of several of these shocks are among the largest known anywhere in the world. Large earthquakes are of thrust type and occur along the plate interface at shallow depth. Large shocks do occur less frequently beneath the deeper part of the trench, at intermediate depths and to the north of the plate boundary in south-central Alaska. The region of Kamchatka demonstrates temporal variation in rupture mode, with occasional very large ruptures spanning segments of the trench that fail individually at other times. In Kurile Islands large earthquakes repeatedly rupture the same portion of the subduction zone, but without coalescing to generate larger events (Lay and Kanamori, 1981).

METHOD APPLIED

Papazachos and Papaioannou (1993) proposed the following relations to describe the time and magnitude predictable model:

$$\log T_t = bM_{min} + cM_p + d\log \dot{M}_o + t \tag{1}$$

$$M_f = BM_{min} + CM_p + D\log \dot{M}_o + m \tag{2}$$

where T_t is the interevent time, measured in years, M_{min} the surface wave magnitude of the smallest mainshock considered, M_p the magnitude of the preceding mainshock, M_f the magnitude of the following mainshock, $\dot{M}_o$ the yearly moment rate in each source. The model expressed by the relations (1) and (2) has the advantage that all parameters (b, c, d, t, B, C, D, m) of these relations are calculated by all available data for all sources.

The moment rate, $\dot{M}_o$, that is, the moment released per year in each seismogenic source is a measure of the seismicity level, and varies from source to source, but it can be reliably calculated if enough data are available for the source. These data concern not only the magnitudes of the few mainshocks but all the complete data of strong and small shocks available for each source. The values of M_o have been determined by applying a method suggested by Molnar (1979). This method makes use of the maximum magnitude, M_{max}, and of the parameters a, b of the Gutenberg and Richter (1944) relation:

$$logN=a-bM \tag{3}$$

normalized for one year, as well as, of the parameters r, k of the moment-magnitude relation:

$$logM_o=rM+k \tag{4}$$

which for the area under study are r=1.5 and k=16.1, according to Kanamori (1977).

For the determination of the coefficients b, c, d, and t of equation (1) one can use a well-known technique (Draper and Smith, 1966; Weisberg, 1980) which has been widely used especially in strong-motion attenuation studies (McGuire, 1978; Joyner and Boore, 1981; Dahle et al., 1990).

SEISMOGENIC SOURCES AND DATA

In order to proceed in the application of the above described methodology, the area under examination was separated in twelve seismogenic sources. For this purpose seismotectonic criteria, dimension of aftershock volumes, seismicity level, maximum earthquake observed, type of faulting and geomorphological criteria were used. The fit of the data to the time-predictable model has been used as a suplementary criterion for this separation.

Along the Alaska-Aleutians five seismogenic sources were defined (Alaska Gulf, Shumagin Islands, Andreanoff Islands, Rat Islands and Kommandorski Islands) on the basis of the spatial distribution of aftershock volumes of great earthquakes, according to Sykes (1971). The above mantioned author mapped the rupture zones of large ($M_s \geq 7.0$) earthquakes along the plate boundary in southern Alaska and Aleutians by relocating aftershocks of those events and by assuming that the latter are a good measure of the area of the rupture surface.

The Kamchatka-Kuriles region was divided in seven seismogenic sources (Northeastern Kamchatka, Southeastern Kamchatka, Shiashkotan Islands, Urup Islands, Etorofu Islands, Shikotan Islands and Kunashir Islands) based both on the spatial distribution of aftershock volumes and the spatial distribution of the larger ($M_s \geq 7.0$) earthquakes.

Figure 1 shows the seismogenic sources along with the epicenters of the larger ($M_s \geq 7.0$) earthquakes. Black circles show epicenters of the mainshocks, while open circles foreshocks or aftershocks. The term 'foreshock' or 'aftershock' is used here in the broad sense, that is, earthquakes which precede or follow mainshocks several years. In particular, as foreshocks or aftershocks are considered the earthquakes which occur 9, 12.5 and 16 years before or after the occurrence of a mainshock with magnitude equal to or larger than 6.0, 7.0 and 8.0, respectively. This was done because we are interested to apply a model which can predict the mainshocks in each seismogenic source, that is, the strong earthquakes which occur at the beggining and the end of each seismic cycle and not smaller earthquakes which occur during the preseismic and postseismic activations.

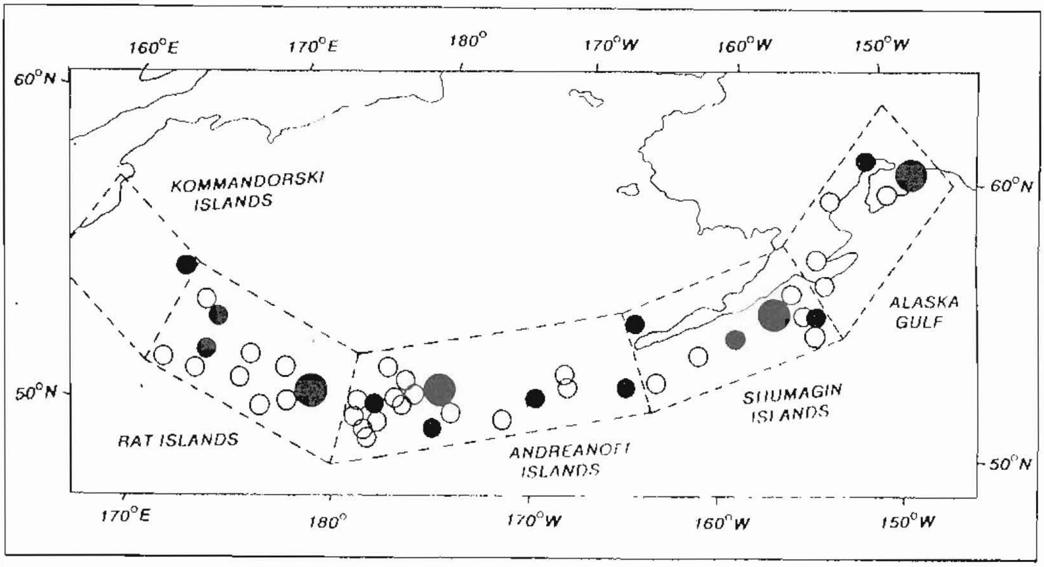

Fig. 1a. The five seismogenic sources in which the area of Alaska-Aleutians was divided along with the epicenters of strong ($M_s \geq 7.0$) shallow mainshocks (black circles) and fore- or aftershocks (open circles) in the broad sense.

Information on the surface wave magnitudes and on the epicentral coordinates of the earthquakes used in the present study were received from the catalogue of Pacheco and Sykes (1992), for events occurred during the present century and with $M_s \geq 7.0$. For events not listed in the previous catalogue, as well as, for events with magnitudes less than 7.0, the catalogues of Abe (1981) and Tsapanos and his colleagues (1990) were used, while for the more recent events the data were according to the ISC bulletins. The final catalogue is complete and homogeneous for events with $M_s \geq 7.0$, during the time period 1897-1992, that is for the time period after the beggining of the world-wide instrumental record in 1897, till now. The comlpeteness for smaller events varies from source to source.

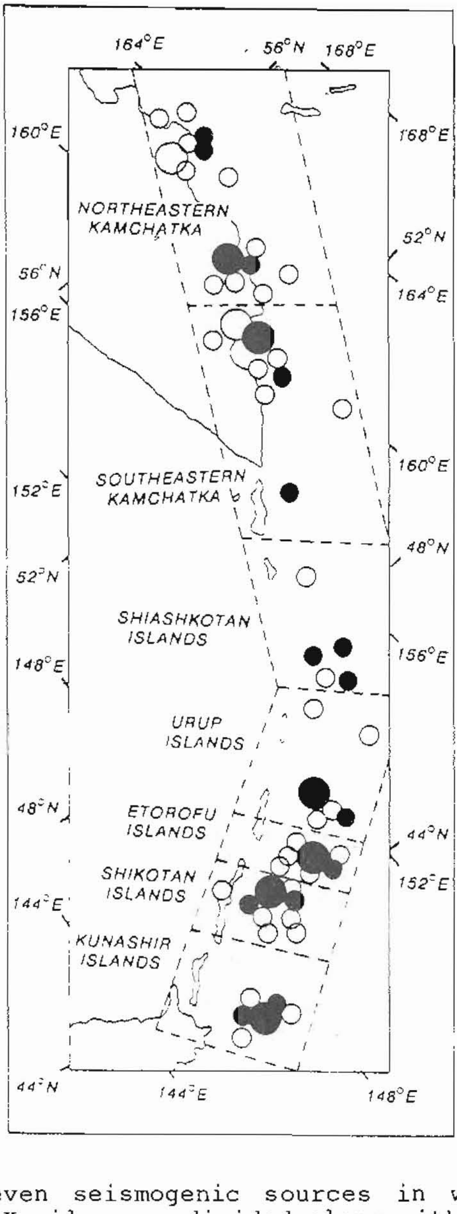

Fig.1b. The seven seismogenic sources in which the area of Kamchatka-Kuriles was divided along with the epicenters of strong ($M_s \geq 7.0$) shallow mainshocks (black circles) and fore- or aftershocks (open circles) in the broad sense.

RESULTS

The procedure suggested by Papazachos and Papaioannou (1993) was followed here in order to estimate the parameters of the relation (1) between the interevent time, T_t, and the magnitudes M_{min} and M_p, and the moment rate. The following relation was found:

$$logT_t=0.30M_{min}+0.15M_p-0.26\log\dot{M}_o+5.24 \qquad (5)$$

with a correlation coefficient equal to 0.70 and a standard deviation equal to 0.17. The positive correlation between the repeat time and the magnitude of the preceding mainshock indicates that the time predictable model holds.

The values of the parameters of the relation (2) were determined and the following empirical formula was obtained:

$$M_f=1.05M_{min}-0.47M_p+0.60\log\dot{M}_o-12.39 \qquad (6)$$

with a standard deviation equal to 0.40 and a correlation coefficient equal to 0.73. The negative value of the parameter C means that large mainshocks are followed by small ones and vice versa.

PREDICTION OF STRONG SHALLOW MAINSHOCKS

In order to proceed in the determination of the probability, P, of occurrence of an earthquake larger than a certain magnitude (e.g. $\geq$7.5) in future predefined time interval, the distribution function, f(t), of the data used must be known. It was found that the quantity $\log(T/T_t)$, where T is the observed and T_t the theoretical repeat time as it is calculated from relation (5), follows a normal distribution with a mean equal to zero and a standard deviation equal to 0.17. This is in accordance with previous investigators found that the lognormal distribution provides better fit to the data of earthquake interevent times (Nishenko and Buland, 1987; Papazachos, 1988b, 1991; Papazachos and Papaioannou, 1993).

Figure 2 shows the frequency function for the quantity $\log(T/T_t)$, concerning the data for all the seismogenic sources examined here, and the theoretical normal distribution. Taking into account that the lognormal distribution holds and considering the time of occurrence of the preceding mainshock in each seismogenic source, the probabilities, P_{10}, of occurrence of the next mainshocks with magnitudes $M_s\geq7.5$ during the next ten years (1993-2003) were calculated.

Table 1 gives information on the expected large ($M_s\geq7.5$) shallow earthquakes. The first column gives the name of the seismogenic source. The other two columns give the probabilities, P_{10}, for the occurrence of large ($M_{min}\geq7.5$) shallow mainshock sduring the next decade (1993-2003) and the corresponding magnitudes, M_f, of the expected earthquakes, as these magnitudes were calculated by the relation (6). The seismogenic sources of Shumagin Islands, Northeastern Kamchatka, Southeastern Kamchatka and Urup Islands exhibit the higher probabilities ($0.51\leq P_{10}\leq0.60$)

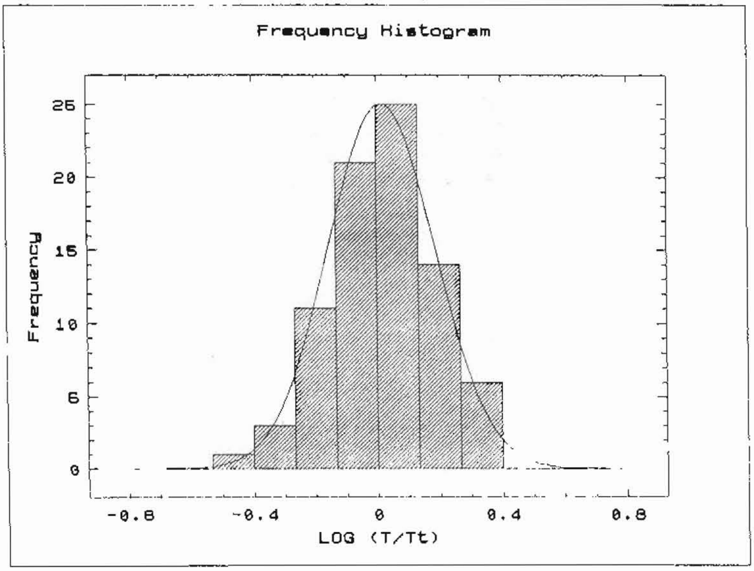

Fig.2. The frequency distribution of the observed repeat times to the theoretical ones.

Table 1. Information on the expected magnitudes, M_f, and the corresponding probabilities, P_{10}, for the occurrence of large ($M_{min} \geq 7.5$) shallow earthquakes during the period 1993-2002 in North Pacific seismic zone.

SEISMOGENIC SOURCE	M_f	P_{10}
SOURCE 1 - ALASKA GULF	7.6	0.43
SOURCE 2 - SHUMAGIN ISLANDS	8.2	0.60
SOURCE 3 - ANDREANOF ISLANDS	8.1	0.25
SOURCE 4 - RAT ISLANDS	7.7	0.48
SOURCE 5 - KOMMANDORSKI ISLANDS	7.7	-
SOURCE 6 - NORTHESTERN KAMCHATKA	8.2	0.51
SOURCE 7 - SOUTHEASTERN KAMCHATKA	8.3	0.52
SOURCE 8 - SHAISHKOTAN ISLANDS	8.1	0.48
SOURCE 9 - URUP ISLANDS	8.0	0.59
SOURCE 10 - ETOROFU ISLANDS	7.6	0.40
SOURCE 11 - SHIKOTAN ISLANDS	7.9	0.33
SOURCE 12 - KUNASHIR ISLANDS	7.5	0.27

for the occurrence of a mainshock with $M_s \geq 7.5$ during the next ten years. High probabilities ($0.43 \leq P_{10} \leq 0.48$) are estimated for Alaska Gulf, Rat Islands and Shiashkotan Islands seismogenic sources. The Andreanoff Islands, Shikotan Islands and Kunashir Islands seismogenic source exhibit the lower probability ($0.33 \leq P_{10} \leq 0.25$), while for the Kammandorski Islands seismogenic source no probability has been estimated, since the larger earthquake occurred there was much smaller that 7.5 (1925, M_s=7.0).

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