AN APPLICATION OF THE TIME- AND MAGNITUDE-PREDICTABLE MODEL FOR THE LONG-TERM PREDICTION OF STRONG SHALLOW EARTHQUAKES IN JAPAN AREA

Papazachos,B.C., Papadimitriou,E., Karakaisis,G., and Tsapanos,T.

Geophysical Laboratory, University of Thessaloniki, GR-54006 Thessaloniki, Macedonia, GREECE.

A B S T R A C T

The interevent times of the strong shallow mainshocks in 12 seismogenic sources in the area of Japan have been determined. Segmentation of the area is delineated by the rupture zones of the largest earthquakes occuring in each seismogenic source. The following relations were determined:

$$\log T_t = 0.30M_{min} + 0.19M_p - 0.18\log\dot{M}_o + 2.41$$

$$M_f = 0.88M_{min} - 0.25M_p + 0.46\log\dot{M}_o - 9.06$$

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.

Time-dependent conditional probabilities for the occurrence of the next large ($M_s \geq 7.5$) shallow mainshocks in the twelve seismogenic sources during the next ten years and the magnitude of the expected mainshock are determined, based on these two relations, and taking into account the time of occurrence and the magnitude of the last mainshock in each seismogenic source.

ΕΦΑΡΜΟΓΗ ΤΟΥ ΧΡΟΝΙΚΑ ΕΞΑΡΤΩΜΕΝΟΥ ΜΟΝΤΕΛΟΥ ΓΙΑ ΤΗ ΜΑΚΡΑΣ ΔΙΑΡΚΕΙΑΣ ΠΡΟΓΝΩΣΗ ΙΣΧΥΡΩΝ ΕΠΙΦΑΝΕΙΑΚΩΝ ΣΕΙΣΜΩΝ ΣΤΗΝ ΠΕΡΙΟΧΗ ΤΗΣ ΙΑΠΩΝΙΑΣ.

Παπαζάχος,Β.Κ., Παπαδημητρίου,Ε., Καρακαΐσης,Γ. και Τσάπανος,Θ.

Π Ε Ρ Ι Λ Η Ψ Η

Οι χρόνοι επανάληψης των ισχυρών επιφανειακών κύριων σεισμών σε 12 σεισμογόνες πηγές στην περιοχή της Ιαπωνίας έχουν υπολογιστεί. Ο χωρισμός της περιοχής σε σεισμογόνες πηγές βασίστηκε στην χωρική κατανομή των εστιακών όγκων των μεγαλύτερων σεισμών. Βρέθηκαν οι παρακάτω σχέσεις:

$$logT_t=0.30M_{min}+0.19M_p-0.18\log\dot{M}_o+2.41$$

$$M_f=0.88M_{min}-0.25M_p+0.46\log\dot{M}_o-9.06$$

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, $\dot{M}_o$ η ετήσια έκλυση της σεισμικής ροπής για κάθε σεισμική πηγή. Με βάση τις παραπάνω σχέσεις, υπολογίστηκαν η πιθανότητα γένεσης των αναμενόμενων ισχυρών επιφανειακών σεισμών ($M_s \geq 7.5$) καθώς και το μέγεθος των σεισμών αυτών, κατά την επόμενη δεκαετία.

INTRODUCTION

Considerable attention has been paid by scientists during the last decades, to find a model concerning the relationship between the slip amount of an earthquake fault and the time of occurrence of a large earthquake. From this viewpoint, the time-predictable and the slip-predictable models have been proposed. According to the time-predictable model the time interval between large earthquakes is proportional to the slip amount of the preceding earthquake, and large earthquakes occur when the stress has reached a fixed limit value. In the slip-predictable model the time interval between large earthquakes is proportional to the slip amount of the next large earthquake.

Bufe and his colleagues (1977) reported that the time-predictable model is well suited to moderate earthquakes along the San Andreas fault in California, and that the time of the next earthquake can be forecasted from the slip amount of the previous earthquake. Shimazaki and Nakata (1980) presented three simplified models concerning the relationship between the slip amount of an earthquake fault and the time of occurrence of a large earthquake, and discussed which of these types resembles the repeated great earthquakes along the Nankai Trough, in Japan. Focusing on the amount of uplift during the Nankaido earthquake, Shimazaki and Nakata (1980) showed that the relationship between the slip amount of the earthquake fault (inferred from the amount of uplift) and the interval between large earthquakes fits the time-predictable model. Mogi (1985) comparing data on seismic activity inland in western Japan, based on historical materials and covering a long period, showed that the temporal changes in the degree of seismic activity of inland earthquakes in western Japan support the time-predictable model, and clearly differ from what was expected from slip-predictable model. Data on both crustal changes and seismic activity show that the time-predictable model is close to the actual cituation. This reveals that great earthquakes along the Nankai Trough have occurred when the stress level over a wide area reaches the ultimate value. Sykes and Quitmeyer (1981) found that data on the geometry, seismic moment and repeat time of large shocks of both the strike-slip and convergent types agree better with the time-predictable model of earthquake reccurrence than with the slip-predictable model.

Papazachos (1988a, 1988b, 1989, 1991, 1992, 1993) carried out an investigation to identify time dependent relations between strong earthquakes which occurred in seismogenic sources in Greece. He proposed a model where the interevent time, T_t, and the magnitude, M_f, of the following mainshock were quantitatively expressed in relation to the magnitude, M_{min}, of the smallest considered mainshock and to the magnitude, M_p, of the preceding mainshock in each seismogenic source, and found that the time-predictable model holds. More recently (Papazachos and Papaioannou, 1993) improved the above methodology 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. Furthermore, they applied this model to estimate the probability of occurrence of the next mainshock during the next ten years and the magnitude of this expected mainshock in each seismogenic source of the Aegean area.

It is evident from all the above cases that the time-predictable model describes better the behavior of seismic activity. An attempt is made in the present paper to establish the validity of that model in the area of Japan, and moreover to estimate the probability of occurrence of the next mainshock in each seismogenic source in which the whole area was divided, as well as, the magnitude of the expected mainshock.

Figure 1 shows the examined area along with its general tectonic characteristics. The Pacific Plate spreading from the East Pacific Rise is subducted beneath the Eurasia Plate at the Aleutian-Kurile-Japan-Mariana Trench system. The Philippine Sea Plate, a subsidiary Plate bounded by two deep sea-canyons, the Nankai and Sagami Troughs, and the Izu-Mariana Island Arc, is moving northwestwards and subducts also under the Eurasia Plate. Most of the large shallow earthquakes in Japan occur due to low-angle thrust fault movements resulting from this subduction, and all occur on the land side of the Trench.

METHOD APPLIED

Papazachos and Papaioannou (1993) based on the interevent times of strong mainshocks in the seismogenic sources of the Aegean area, found the following relations:

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

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

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 moment rate in each source per year.

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, M_0, that is, 'the moment released per year in each seismogenic source is a measure of the seismicity level, and varies form 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_0 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:

$$logN = a - bM \qquad (3)$$

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

$$logM_o = rM + k \qquad (4)$$

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).

THE SEISMOGENIC SOURCES AND DATA USED

The whole area was separated, for the purposes of the present study, in 12 seismogenic sources. This division was based on seismotectonic criteria, dimension of aftershock volumes, seismicity level, maximum earthquake observed, type of faulting and geomorphological criteria. The fit of the data of each source to the time-predictable model has been used as a suplementary criterion for this separation.

The main tectonic characteristics of the area under study is the Ryukyu Trench, the Nankai Trough, the Sagami Trough, the Japan Trench and the Hokkaido-Kurile Trench. We have not defined a seismogenic source to belong in different tectonic segments, but along these major lines. The dimensions of the sources are comparable to the rupture zone of the maximum earthquake that has occurred there. The rupture zones are estimated on the basis of the spatial extent of aftershock area for recent earthquakes and from historical documents (Mogi, 1985). It is possible, one seismogenic source to have been ruptured in smaller segments, but there is not a seismogenic source smaller that the maximum aftershock volume ever reported.

Along the Ryukyu Trench two seismogenic sources were defined on the basis of the spatial distribution of the epicenters of the largest ($M_s \geq 7.0$) earthquakes, the "Ryukyu Islands" source (1 in Fig. 1) and the "Kyushu" source (2 in Fig. 1). The Nankai Trough is considered as one seismogenic source (3 in Fig. 1), since it has been struck by the giant 1707 Hoei earthquake. The Sagami Trough, which forms the boundary between the Philippine Sea Plate and the Eurasia Plate and characterized by right lateral strike-slip thrust-type earthquakes (Mogi, 1985) is considered as one seismogenic source (4 in Fig. 1).

An extremely active seismic belt runs along the Japan Trench from the Kurile Trench. This activity is due to the Pacific Plate subducting westwards under the Japanese Islands at this trench axis. Two seismogenic sources have been defined here, the "Fukushima" source (5 in Fig. 1) and the "Tohoku" seismogenic source (6 in Fig. 1) which coincides with the seismogenic volume of the great 1933 Sanriku-Oki earthquake, which was the largest earthquake that occurred in or around the Japanese Islands this century. According to Kanamori (1971), this earthquake occurred as the result of normal faulting due to the rupture of the subducting Pacific Plate.

The focal regions of great earthquakes that have occurred this century from the northern Japan Trench across to the southern Kurile Trench, almost completely cover the seismic zone with virtually no overlapping at all. These great earthquakes occur because shearing strain is suddenly released when the Pacific Plate collides with the Eurasian Plate and subducts beneath it. The division of Utsu (1972), based on the aftershock volumes occurred along the Trench, is followed here to define two seismogenic sources: the "South Hokkaido" seismogenic source (7 in Fig. 1) and the "North Hokkaido" seismogenic source (8 in Fig. 1).

In the inner part of the examined area, three other seismogenic sources were defined. In the western part of Honshu Island, one seismogenic source is defined, on the basis of the clustering of the large ($M_s \geq 7.0$) earthquakes which is called "Western Honshu" seismogenic source (9 in Fig. 1). The "Niigata" seismogenic source (10 in Fig. 1) and the "Japan Sea" seismogenic source (11 in Fig. 1) were defined according to the spatial distribution of epicenters and the dimensions of the aftershock volumes of the recent large earthquakes (1964-Niigata M_s=7.5 and 1983-Japan Sea M_s=7.7 mainshocks). Futher northwards, the source 12 (Okusluri island) includes the focal area of the 1940 earthquake (Mogi, 1985).

Figure 1 shows the definition of the 12 seismogenic sources along with the epicenters of all the earthquakes with $M_s \geq 7.0$ which occurred during the time period that our catalogue covers. Black circles show epicenters of mainshocks. Open circles show epicenters of foreshocks and aftershocks in the broad sence, that is, earthquakes, within the complete sample of data, which may occur up to several years before or after the mainshocks, respectively. We use the terms "aftershock" and "foreshock" in their broad sence because in the present paper we want a model which can predict the mainshocks in each seismogenic source, that is, the strong earthquakes which occurred at the beginning and the end of each seismic cycle and not smaller earthquakes that occur during the preseismic and postseismic activation. This is in accordance with Mogi (1985) suggesting that seismic activity over a wide area would increase through a rise in crustal stress, and that these shocks are foreshocks in the broad sence. In particular, we consider as foreshocks or aftershocks the earthquakes which precede or follow mainshocks with magnitudes 6.5-7.0, 7.1-7.9 and larger than 7.9 up to 9, 12.5 and 15 years, respectively.

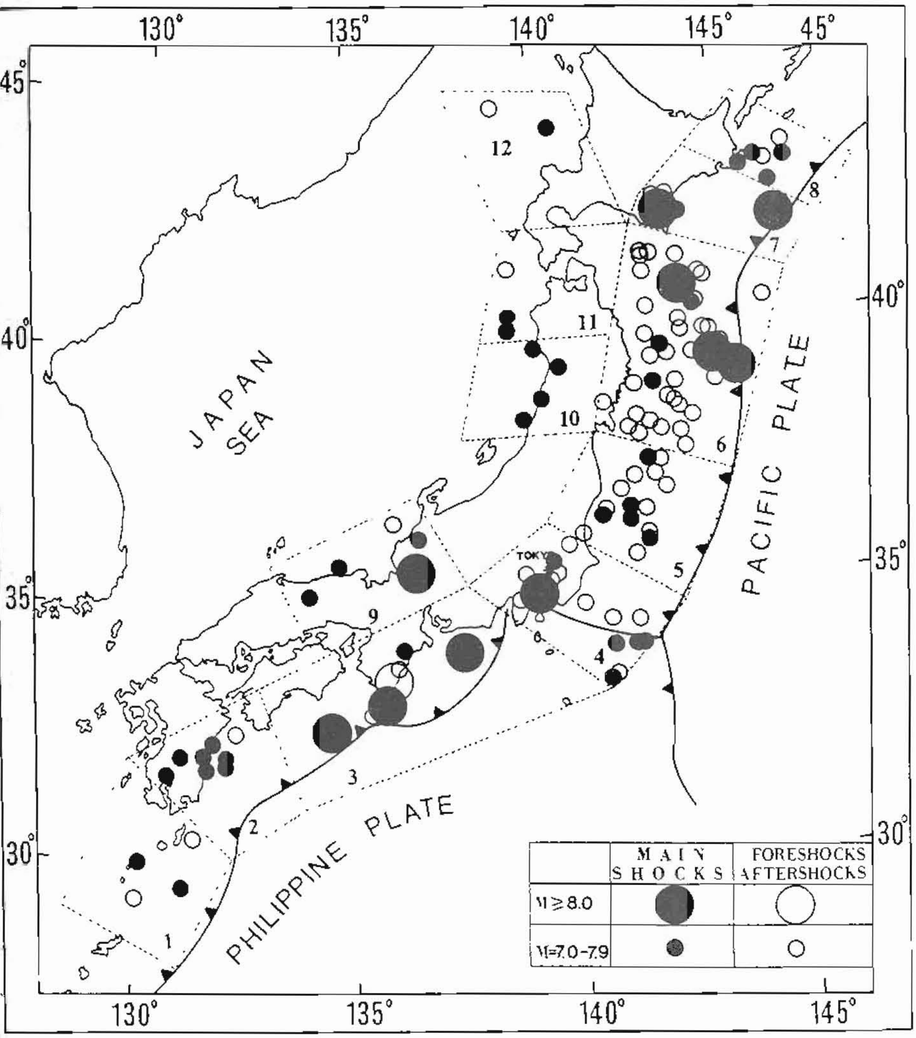

Fig.1. The twelve seismogenic sources in which the area of Japan was divided along with the epicenters of strong ($M_s \geq 7.0$) shallow mainshocks (black circles) and fore- or aftershocks (open circles) in the broad sense.

Information on the surface wave magnitudes and on the epicenters plotted in Figure 1 were received from the catalogue of Pacheco and Sykes (1992) for events occurred during the present century with $M_s \geq 7.0$. The magnitudes of historical events have been received from Rikitake (1976, 1982). For the time period 1885-1900 the catalogue of Utsu (1988) was used. For events not listed in the previous catalogues, 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 magnitudes were checked by the ISC bulletins.

RESULTS

The procedure suggested by Papazachos and Papaioannou (1993) was followed here in order to estimate the parameters of the relation (1) between the repeat time, T, and the magnitudes M_{min} and M_p, and the moment rate. For this purpose, data which concern the 11 seismogenic sources, with a total number of 69 repeat times, and were used to determine the relation:

$$logT_t = 0.30M_{min} + 0.19M_p - 0.18\log\dot{M}_o + 2.41 \qquad (5)$$

with a correlation coefficient equal to 0.68 and a standard deviation equal to 0.19. 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:

$$M_f = 0.88M_{min} - 0.25M_p + 0.46\log\dot{M}_o - 9.06 \qquad (6)$$

with a standard deviation equal to 0.34 and a multilinear correlation coefficient equal to 0.84. The negative value of C means that large mainshocks are followed by small ones and vice versa. Papazachos (1992) and Papazachos and Papaioannou (1993) also arrived in the same conclusion for earthquakes in Greece.

LONG TERM PREDICTION OF THE NEXT SHALLOW MAINSHOCK

The validity of the model established in the present study, provides a mean to calculate the time of occurrence of the next large mainshock in each one of the defined seismogenic sources, by relation (5). However, since there is a considerable difference between repeat times, T_t, estimated from (1) in respect to the corresponding actual repeat times, T, it is preferable to estimate the probability of occurrence of the next mainshock larger than a certain magnitude and in a given time interval.

Previous attempts to apply probabilistic methods for forecasting future earthquake occurrence have used either Gaussian distribution (Lindh, 1983; Sykes and Nishenko, 1984) or Weibull distributions (Rikitake, 1976; Nishenko, 1985). More recently, Nishenko and Buland (1987) investigated the utility of the simple function T/T_{ave}, to help define the overall distribution properties of earthquake recurrence, where T_{ave} is the average recurrence interval observed for a specific fault or plate boundary segment, and T is an individual recurrence interval. They found that the lognormal distribution provides better fit to the T/T_{ave} data than the previous used Gaussian or Weibull distributions. Papazachos (1988b, 1991, 1993) and Papazachos and Papaioannou (1993) have also found the lognormal distribution of T/T_t as more appropriate for data concerning the occurrence of earthquakes in the area of Greece.

Figure 2 shows a histogram of $\log(T/T_t)$ values were T is the actual repeat times and T_t is the theoretical repeat times. The $\log(T/T_t)$ is normally distributed with a mean equal to zero and a standard deviation of 0.19. Given the date of the last event in a seismogenic source, the probability of a occurrence of the next shallow mainshock with $M_s \geq 7.5$, during the next 10 years were computed.

Table 1 gives information on the expected large ($M_s \geq 7.5$) shallow earthquakes based on the model expressed by the relation (5). The first column gives the name of the seismogenic source. The other two columns give the highest probabilities, P_{10}, for the occurrence of large ($M_{min} \geq 7.5$) during the next decade (1993-2002) and the corresponding magnitudes, M_f, of the expected earthquakes, as these magnitudes were calculated by the relation (6). The seismogenic sources of Fukushima, southern Hokkaido, Ryukyu islands, Okushiri and Western Honshu, exhibit high probabilities ($P_{10} \geq 0.5$) for the occurrence of an earthquake with $M_s \geq 7.5$ during the next ten years. Intermediate values ($0.46 \leq P_{10} \leq 0.33$) are estimated for the seismogenic sources of Kyushu Island, Nankai Trough, Sagami Trough, N. Hokkaido and Niigata. Low probability ($P_{10}=0.22$) was found for Tohoku seismogenic source, and finaly, very low probability for the north part of Japan Sea ($P_{10}=0.08$).

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 Japan.

Seismogenic Source	$M_{min} \geq 7.5$	
	M_f	P_{10}
SOURCE 1 - RYUKYU ISLANDS	7.6	0.49
SOURCE 2 - KYUSHU	7.8	0.46
SOURCE 3 - NANKAI	7.4	0.37
SOURCE 4 - SAGAMI	7.9	0.43
SOURCE 5 - FUKUSHIMA	8.0	0.62
SOURCE 6 - TOHOKU	8.2	0.22
SOURCE 7 - S. HOKKAIDO	7.8	0.52
SOURCE 8 - N. HOKKAIDO	7.6	0.33
SOURCE 9 - W. HONSHU	8.0	0.62
SOURCE 10 - NIIGATA	7.5	0.41
SOURCE 11 - JAPAN SEA	7.5	0.08
SOURCE 12 - OKUSHIRI	7.5	0.49

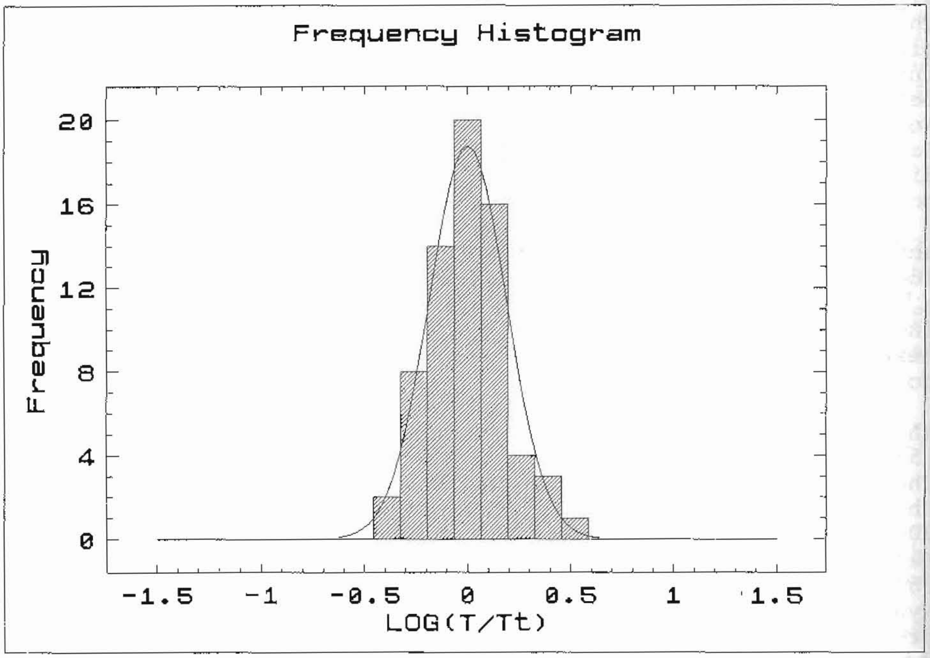

Fig.2. The frequency distribution of the observed repeat times to the theoretical ones.

AKNOWLEDGEMENTS

A computer program for determination of the parameters of the relations (5), (6), written by C. Papazachos, another one for distinguishing foreshocks and aftershocks, written by E. Scordilis and a third for the calculation of the probabilities, written by C. Papaioannou, were used. The authors would like to express their sincere appreciation to all of them.

REFERENCES

Abe,K., (1981). Magnitudes of large earthquakes from 1904 to 1980, Phys. Earth. Planet. Interiors 27, 72-93.

Bufe,C.G., Harsh,P.W. and Burford,R.O., (1977). Steady-state seismic slip: A precise recurrence model, Geophys. Res. Lett. 4, 91-94.

Dahle,A., Bungum,H. and Kramme,L., (1990). Attenuation models inferred from intraplate earthquake recordings, Earthq. Eng. Struct. Dynam. 19, 1125-1141.

Draper,N.R. and Smith,H., (1966). Applied regression analysis, Wiley, New York, 407pp.

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

Joyner,W.B. and Boore,D.M., (1981). Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California earthquake, Bull. Seism. Soc. Am. 71, 2011-2038.
Kanamori,H., (1971). Seismological evidence for a lithospheric normal faulting - the Sanriku earthquake of 1933, Phys. Earth Planet. Inter. 4, 289-300.
Kanamori,H., (1977). The energy released in great earthquakes, J. Geophys. Res. 82, 2981-2987.
Lindh,A.G., (1983). Preliminary assessment of long-term probabilities for large earthquakes along selected fault segments of the San Andreas fault system in California, U. S. Geol. Surv., Open-File Rept. 83- 63, 1-15.
McGuire,R., (1978). Seismic ground motion parameter relation, Proc. ASCE J. Geotech. Eng. Div. 104, 481-490.
Mogi,K., (1985). Earthquake Prediction, Academic Press pp. 355.
Molnar,P., (1979). Earthquake recurrence intervals and plate tectonics, Bull. Seism. Soc. Am. 69, 115-133.
Nishenko,S.P., (1985). Seismic potential for large and great interplate earthquakes along the Chilean and Southern Peruvian margins of South America: A quantitative reappraisal. J. Geophys. Res. 90, 3589-3615.
Nishenko,S.P. and Buland,R., (1987). A Generic recurrence interval distribution for earthquake forecasting, Bull. Seism. Soc. Am. 77, 1382-1399.
Pacheco,J.F. and Sykes,L.R., (1992). Seismic moment catalog of large shallow earthquakes, 1900 to 1989, Bull. Seism. Soc. Am. 82, 1306-1349.
Papazachos,B., (1988a). Seismic hazard and long-term earthquake prediction in Greece, European School of Earthquake Sciences, Course on Earthquake Hazard Assessment, Athens, 9-16 May 1988, pp. 1-10.
Papazachos,B., (1988b). Long-term prediction of earthquakes in seismogenic sources of Greece, United Nations Seminar on the Prediction of Earthquakes, Lisbon, Portugal, 14-18 November 1988, 77-84.
Papazachos,B.C., (1989). A Time-predictable Model for Earthquakes in Greece, Bull. Seism. Soc. Am. 79, 77-84.
Papazachos,B.C., (1991). Long term earthquake prediction in south Balkan region based on a time predictable model, 1st Gen. Conf. of the B. P. U., Thessaloniki, Sept. 26-28, 1991, 1-11.
Papazachos,B.C., (1992). A time- and magnitude-predictable model for generation of shallow earthquakes in the Aegean area. Pure Appl. Geophys. 138, 287-308.
Papazachos,B.C., (1993). Long term prediction of intermediate depth earthquakes in southern Aegean region based on a time-predictable model, Natural Hazards, 7, 211-218.
Papazachos,B.C. and Papaioannou,Ch.A., (1993). Long term earthquake prediction in the Aegean area based on a time and magnitude predictable model, Pure Appl. Geophys. (in press).
Rikitake,T., (1976). Recurrence of great earthquakes at subduction zones, Tectonophysics 35, 335-362.
Rikitake,T., (1982). Current research in earthquake prediction I, Reidel Publ. Co. pp. 383.

Shimazaki,K. and Nakata,T., (1980). Time-predictable recurrence model for large earthquakes, Geophys. Res. Lett. 7, 279-282.
Sykes,L.R. and Quitmeyer,R.C., (1981). Repeat times of great earthquakes along simple plate boundaries, In: Earthquake Prediction, An Intern. Review (eds. Simpson, D.W. and Richards, P.G.) (Maurice Ewing Series, Amer. Geophys. Union 1981 4, 217-247.
Sykes,L.R. and Nishenko,S.P., (1984). Probabilities of occurrence of large plate rupturing earthquakes for the San Andreas, San Jacinto and Imperial faults, California, 1983-2003, J. Geophys. Res. 89, 5905-5927.
Tsapanos,T.M., Scordilis,E.M. and Papazachos,B.C., (1990). A global catalogue of strong earthquakes, Publ. Geophys. Lab. Univ. Thessal. 9, pp. 90.
Utsu,T., (1972). Large earthquakes near Hokkaido and the expectancy of the occurrence of a large earthquake off Nemuro, Rep. Coord. Comm. Earthquake Prediction 7, 7-13.
Utsu,T., (1988). A catalogue of large earthquakes ($M \geq 6$) and damaging earthquakes in Japan for the years 1885-1925, In: Historical seismograms and earthquakes of the world (eds. Lee,W.H.K., Meyers,H. and Shimazaki,K.), Academic Press, 150-161.
Weisberg,S., (1980). Applied linear regression, Wiley New, York, 283pp.