LONG TERM EARTHQUAKE PREDICTION IN THE PHILIPPINES REGION BASED ON THE TIME AND MAGNITUDE PREDICTABLE MODEL

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ABSTRACT

Instrumental and historical information on strong mainshocks in 22 seismogenic sources of the Philippines area have been used to show that the interevent time, T_t (in years), between two strong earthquakes and the magnitude, M_f, of the following mainshock are given by the relations:

$$\mathrm{Log}T_t = 0.15M_{min}+0.17M_p-0.27\log\dot{M}_o+5.98$$

$$M_f = 0.77M_{min}-0.43M_p+0.68\log\dot{M}_o-12.81$$

where M_{min} is the surface wave magnitude of the smallest mainshock considered, M_p the magnitude of the preceding mainshock and M_o the moment rate per year in each source. On the basis of these relations, the probability for the occurrence of a mainshock during the decade 1993-2002 as well as the magnitude of this expected mainshock in each seismogenic source have been calculated.

ΜΑΚΡΟΠΡΟΘΕΣΜΗ ΠΡΟΓΝΩΣΗ ΣΕΙΣΜΩΝ ΣΤΗΝ ΠΕΡΙΟΧΗ ΤΩΝ ΦΙΛΙΠΠΙΝΩΝ, ΒΑΣΙΣΜΕΝΗ ΣΤΟ ΜΟΝΤΕΛΟ ΠΡΟΓΝΩΣΗΣ ΤΟΥ ΧΡΟΝΟΥ ΚΑΙ ΤΟΥ ΜΕΓΕΘΟΥΣ ΤΩΝ ΙΣΧΥΡΩΝ ΣΕΙΣΜΩΝ

Παναγιωτόπουλος,Δ.

ΠΕΡΙΛΗΨΗ

Ενόργανα και ιστορικά δεδομένα ισχυρών επιφανειακών σεισμών σε 22 σεισμογόνες πηγές της περιοχής των Φιλιππίνων χρησιμοποιήθηκαν για να δειχθεί ότι ο χρόνος, T_t, του σεισμού που ακολουθεί δίνονται από τις σχέσεις:

$$\mathrm{Log}T_t = 0.15M_{min}+0.17M_p-0.27\log\dot{M}_o+5.98$$

$$M_f = 0.77M_{min}-0.43M_p+0.68\log\dot{M}_o-12.81$$

όπου M_{min} είναι το επιφανειακό μέγεθος του μικρότερου κύριου σεισμού που θεωρούμε, M_p το μέγεθος του κυρίου σεισμού που προηγήθηκε και M_o η ετήσια έκλυση της σεισμικής ροπής για κάθε σεισμική πηγή. Με βάση τις σχέσεις αυτές υπολογίσθηκαν η πιθανότητα γένεσης ενός κύριου σεισμού κατά τη δεκαετία 1993-2002 καθώς και το μέγεθος αυτού του αναμενόμενου σεισμού σε κάθε

σεισμογόνο πηγή της περιοχής των Φιλιππίνων.

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 small faults where smaller mainshocks also occur (Papazachos, 1989).

According to the time-predictable model, the time of occurrence of a future earthquake in a certain seismogenic source depends on the size 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 principal, 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).

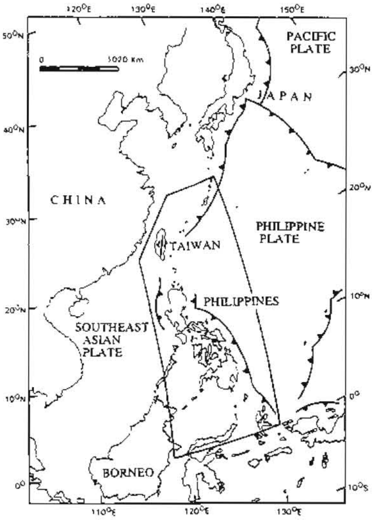

Fig.1. The studied area (modified from Hanilton, 1977; Allen, 1962; Rowlett and Kelleher, 1976).

Very recently, Papazachos(1988a,b, 1989, 1991, 1992, 1993) concluded that the time-predictable model holds very well for the strong shallow 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 related with the magnitude, M_{min}, of the smallest mainshock considered and with the magnitude, M_p, of the preceding mainshock in each seismogenic source. In addition Papazachos and Papaioannou (1993), improving this idea, included a new term in this methodology, which depends on the yearly moment rate in each seismogenic source. They applied this model to estimate the probability of occurrence of the next mainshock in the next decade and the magnitude of this shock for each seismogenic source of the Aegean area. This is called time and magnitude predictable model.

In the present study we try to test the applicability of the time and magnitude predictable model in the area of Philippines with data from shallow earthquakes. Figure 1 shows the studied area along with its main 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 and the Philippine Plate is moving north-westward and subducts also beneath the south-east Eurasia Plate (Allen, 1962; Fitch, 1972; Rowlett and Kalleher, 1976; Hamilton, 1977).

METHOD

On the basis of the interevent times of strongs mainshocks in the seismogenic sources in Greece, Papazachos and Papaioannou (1993) proposed the following relations:

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

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

where T_t is the interevent time (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 and $\dot{M}_o$ the moment rate in each source per year. We have to note that all parameters (b, c, d, t, B, C, D, m) of the relations 1 and 2 are calculated by all available data for all sources in the studied area.

The moment rate $\dot{M}_o$ can be reliably calculated if enough data are available for the source because it varies from source to source. We use not only the magnitudes of the few mainshocks but all the complete data, that is, all the strong and small shocks which are available for each source. We determined the values of the moment rate $\dot{M}_o$ by applying a method suggested by Molnar (1979). Using this method, the moment rate was calculated on the basis of the maximum magnitude, M_{max}, and of the parameters a and b of the Gutenberg and Richter (1944) relation:

$$\mathrm{Log}N = a - bM \qquad (3)$$

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

$$\mathrm{Log}M_o = rM + k \qquad (4)$$

which for the studied area are r=1.5 and k=16.1 according to Kanamori (1977). On the basis of a well known technique (Weisberg, 1980) which has been used in strong motion attenuation (McGuire, 1978) we determined the coefficients of b, c, d and t of the relation 1, by using a computer program written by C. Papazachos.

SEISMOGENIC SOURCES AND DATA

For the purposes of the present study we separated the whole area in 22 seismogenic sources. This separation was based on seismotectonic criteria, dimension of aftershocks volumes, seismicity level, maximum earthquake observed, type of faulting and geomorphological criteria.

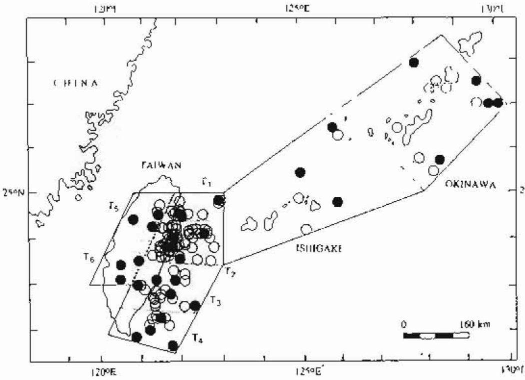

Fig.2. The seismogenic sources in which the nothern part of Philippines area was divided along with the epicentres of strong ($M_s \geq 6.0$) shallow mainshocks (black circles) and fore- or aftershocks (open circles) in their broad sense.

The main tectonic features of the studied area are the Ryukyu trench, the Okinawa trough the Longitudinal Valley Fault in Taiwan, the Luzon trough, the Manila trench, the Philippines trench, the Negros trench, the Celebes trench and the trace of the Philippine mega-fault system (Hamilton, 1977; Gervasio, 1966, 1971; Allen, 1962). We have to note that several large earthquakes have occurred during the last 100 years along these tectonic lines. The dimensions of the sources are in accordance with the rupture zones of the maximum earthquakes that have occurred in these sources.

Between the Okinawa Trough and Ryukyu Trench two seismogenic sources were defined on the basis of the spatial distribution of the epicenters of the largest ($M_s \geq 6.0$) mainshocks and bathymetric features. The two sources are the "Okinawa" and "Ishigaki" sources as are shown in figure 2.

The Longitudinal Valley fault in Taiwan is an active fault and shows both reverse and left-lateral strike slip movement (Allen, 1962; York, 1976). It is located along the east coast of Taiwan and is believed that represents the suture of the arc-continent collision (Lee et al., 1978a; Barrier and Angelier, 1986; Pelletier and Stephan, 1986). Because of tectonic complexity the region of Taiwan is devided in six seismogenic sources (T_1, T_2, T_3, T_4, T_5 and T_6 in fig. 2) and we have to note that much of the activity is located on the "oceanic" side of the Longitudinal fault.

The Luzon strait between the northern Philippines and Taiwan consists of a series of ridges and troughs. Karig (1973) and Rowlett and Kelleher (1976) suggest that plate motion in this region is accommodated by regional release of tectonic strain and that sharp plate boundaries have not yet developed. On the basis of that the Luzon strait is considered as one seismogenic source (L_1 in fig. 3).

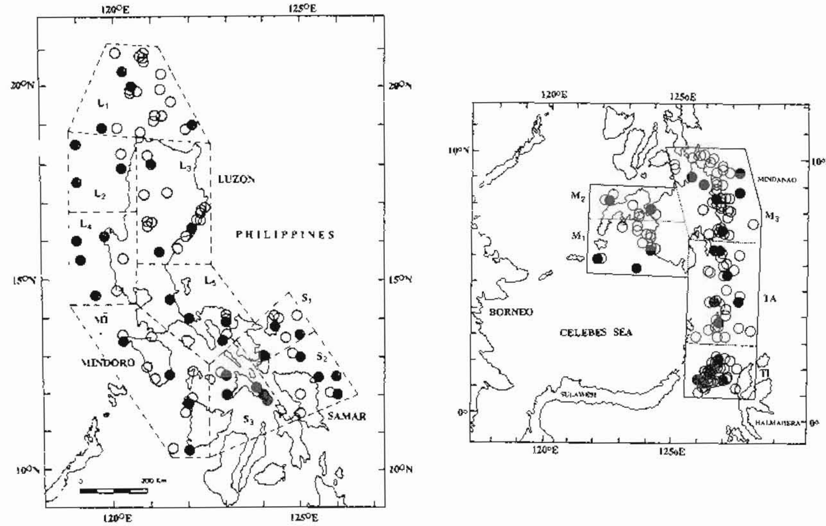

Fig.3. The seismogenic sources in which the central and southern part of Philippines area was divided along the epicentres of strong ($M_s \geq 6.0$) shallow mainshocks (black circles) and fore- or aftershocks (open circles) in their broad sense.

The Manila trench at the western coast of Luzon island is associated with a poorly developed seismic zone and is considered as two seismogenic sources (L_2, L_4 in fig. 3). This separation was based on the spatial distribution of the epicenters of mainshocks ($M_s \geq 6.0$), as well as on the seamounts and other bathymetric features on the underthrusting plate to the west of Luzon.

Focal mechanism solutions of shallow shocks along the east coast of northern Luzon (McCann et al., 1979; Karig, 1973) which do not appear to be associated with the Philippines fault system, indicate westerly-directed underthrusting. On the basis of this we considered this region as one seismogenic source (L_3) as shown in figure 3. The Mindoro region is considered as one seismogenic source (MI in fig. 3) since it has been struck by the strong 1948 (M_s=8.0) Panay earthquake.

The Philippines mega-fault system extends from Mindanao to central Luzon (Gervasio, 1966,1971; McCann et al., 1979), where it branches into several subparallel faults. Fitch (1972) proposed that oblique convergence of the Philippine and Eurasia plates may result in thrust motion at the Philippine trench and left-lateral and strike-slip motion along the Philippine fault. Along this basic tectonic line we considered five seismogenic sources (L_5, S_1, S_2, S_3 and M_3 in fig. 3). This division was based on the spatial distribution of the mainshocks and their foreshocks and aftershocks as well as on basic geomorphological, tectonic and bathymetric features. In the same way the western part of Mindanao is considered as two seismogenic sources (M_1, M_2 in fig. 3).

Along the tectonic line from Mindanao to Halmahera which is the southern part of the collision's boundary between the Philippine plate and south-east Eurasia plate two seismogenic sources (TA and TI in fig. 3) were defined according to the bathymetric feature and the spatial distribution of the epicenters of large shocks (p.e. 1924-SE Mindanao M_s=8.1, 1932-Tifore M_s=7.8).

These twenty two seismogenic sources are shown in fig. 2 and 3, along with the epicenters of the complete data of the shallow earthquakes which are used in the present study. Black circles show epicenters of the main shocks. Open circles show epicenters 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 "foreshocks" and "aftershocks" in their broad sense because we want a model which can predict the main shocks ,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 surface wave magnitudes 5.5-5.7, 5.8-6.0, 6.1-7.0, and larger than 7.0, up to 6, 7, 9 and 12.5 years respectively (Papazachos, 1992). Information on the magnitudes and on the epicenters of the earthquakes plotted in fig. 2 and 3 were taken from the catalogue of Pacheco and Sykes (1992) for events occurred during the present century with $Ms \geq 7.0$. The magnitudes of historical events and for events not listed in the previous catalogue, as well as, for events with magnitudes less than 7.0 have been obtained from Abe (1981), Abe and Noguchi (1983), Gutenberg and Richter (1954), Lee et al., (1978b), Valenzuela and Garcia (1988) and Tsapanos et al. (1990). In addition the more recent events, for the period 1986-1992, were checked up by ISC bulletins.

RESULTS

According to the procedure which suggested by Papazachos and Papaioannou (1993) we used the data from the twenty five seismogenic sources in order to estimate the parameters of the relation 1 between the repeat times T_t, the magnitudes M_{min} and M_p and the moment rate with a total number of 107 repeat times were used to determine the relation:

$$\mathrm{Log}T_t = 0.15M_{min} + 0.17M_p - 0.27\log\dot{M}_0 + 5.98 \qquad (5)$$

with a correlation coefficient equal to 0.61 and a standard deviation equal to 0.16. The positive correlation between the repeat time and the magnitude M_p indicates that the time-predictable model holds very well. In addition we determined the parameters of the relation 2 and the following empirical formula was obtained:

$$M_f = 0.77M_{min} - 0.43M_p + 0.68\log\dot{M}_o - 12.81 \qquad (6)$$

with a standard deviation equal to 0.30 and a correlation coefficient equal to 0.85. The meaning of the negative value C (-0.43) is that large mainshocks are followed by small ones and vice versa.

LONG TERM EARTHQUAKE PREDICTION IN PHILIPPINES AREA

Papazachos (1988b, 1991, 1993) and Papazachos and Papaioannou (1993) have proposed that the lognormal distribution of the ratio T/T_t, where T are the observed interevent times between successive mainshocks in a certain seismogenic source and T_t is the corresponding theoretical value given by relation 1, provides a better fit than the Gaussian and Weibull distributions.

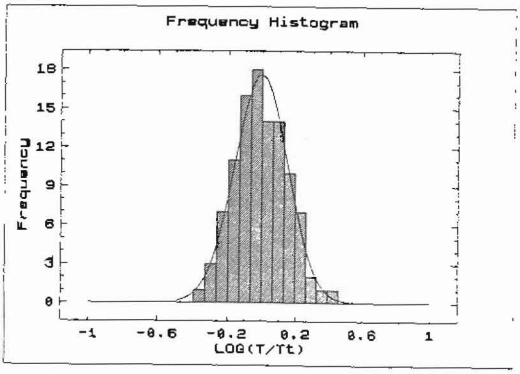

Fig.4. The frequency distribution of the observed repeat times compared to the theoretical one.

Previous researchers were applied probabilistic methods for predicting future mainshocks occurrence by the use of either Gaussian (Lindh, 1983;) or Weibull distribution (Rikitake, 1976). Recently Nishenko and Buland (1987) found that the lognormal distribution fits better to the T/T_a data than the Gaussian or Weibull ones, where T_a is the average recurrence interval observed for a specific fault or plate boundary segment and T is an individual recurrence interval.

Figure 4 displays the frequency histogram of $\mathrm{Log}(T/T_t)$ and the theoretical normal distribution which has a mean equal to zero and standard deviation equal to 0.16. Assuming that the lognormal distribution holds for the area under study and taking into account the time of occurrence and the magnitude of the last main shock, the probabilities of occurrence during the next decade (1993-2003) for earthquakes with magnitudes equal to or larger than 7.0 were calculated. These probabilities are given in table 1 with the corresponding magnitudes M_f of the expected mainshocks as these magnitudes were calculated by the relation 6.

Table 4. Information on the expected shallow earthquakes with magnitudes, M_f, and the corresponding probabilities, P_{10}, for the occurrence of large ($M_s \geq 7.0$) ones during the period 1993-2002 in the Philippines area.

SEISMOGENIC SOURCE	M_f	P_{10}
SOURCE 1 OKINAWA	7.3	0.64
SOURCE 2 ISHIGAKI	7.1	0.61
SOURCE 3 TAIWAN (T1)	7.2	0.61
SOURCE 4 TAIWAN (T2)	7.2	0.37
SOURCE 5 TAIWAN (T3)	7.4	0.60
SOURCE 6 TAIWAN (T4)	7.3	0.40
SOURCE 7 TAIWAN (T5)	7.2	0.65
SOURCE 8 TAIWAN (T6)	6.9	0.59
SOURCE 9 LUZON (L1)	6.9	0.43
SOURCE 10 LUZON (L2)	7.1	0.75
SOURCE 11 LUZON (L3)	7.0	0.04
SOURCE 12 LUZON (L4)	7.1	0.61
SOURCE 13 LUZON (L5)	7.1	0.70
SOURCE 14 MINDORO (MI)	7.3	0.18
SOURCE 15 SAMAR (S1)	6.7	0.19
SOURCE 16 SAMAR (S2)	7.2	0.70
SOURCE 17 SAMAR (S3)	7.1	0.69
SOURCE 18 MINDANAO (M1)	7.3	0.77
SOURCE 19 MINDANAO (M2)	7.1	0.59
SOURCE 20 MINDANAO (M3)	7.2	0.06
SOURCE 21 TALAUD (TA)	8.1	0.86
SOURCE 22 TIFORE (TI)	7.2	0.37

The seismogenic source of Talaud (TA) exhibit very high probability $P_{10}=0.86$ for the occurrence of a strong earthquake with $M_s \geq 7.0$ during the next decade (1993-2003). High probabilities ($0.65 \leq P_{10} < 0.80$) are estimated at the seismogenic sources of Taiwan (T_5), Luzon (L_2, L_5), Samar (S_2, S_3) and Mindanao (M_1). Intermediate values ($0.40 \leq P_{10} < 0.65$) are estimated at the seismogenic sources of Okinawa, Ishigaki, Taiwan (T_1, T_3, T_4, T_6), Luzon (L_1, L_4) and Mindanao (M_2). Finally low probabilities ($P_{10} < 0.40$) are estimated at the seismogenic sources of Taiwan (T_2), Luzon (L_3), Mindoro (MI), Samar (S_1), Mindanao (M_3) and Tifore (TI). The magnitudes of the expected mainshocks (table 4) at the sources Taiwan (T_6), Luzon (L_1) and Samar (S_1) are less than 7.0. In this case we consider that these magnitudes are around the error levels.

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REFERENCES

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

Abe,K. and Noguchi,S., (1983). Revision of magnitudes of large shallow earthquakes, 1897-1912, Phys. Earth Planet. Interiors, 33, 1-11.

Allen,C.R., (1962). Circum-Pacific faulting in the Philippines-Taiwan region, J. Geophys. Res., 67, 4795-4811.

Astiz,L. and Kanamori,H., (1984). An earthquake doublet in Ometepec, Guerrero, Mexico, Phys. Earth. Planet. Interiors, 34, 24-45.

Barrier,E. and Angelier,J., (1986). Active collision in eastern Taiwan: The coastal range, Tectonophysics, 125,39-72.

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.

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

Gutenberg,B. and Richter,C.F., (1954). Seismicity of the Earth and associated phenomena, 2nd ed., Princeton University Press, Princeton, N.J., 310pp.

Fitch,T.J., (1972). Plate convergence, transcurrent faults, and internal deformation adjacent to south-east Asia and the western Pacific, J. Geophys. Res., 77, 4432-4460.

Gervasio,F., (1966). Age and nature of orogenesis of the Philippines, Philipp. Geol., 20, 121-140.

Gervasio,F., (1971). Geotectonic development of the Philippines, J. Geol. Soc. Philipp., 25, 18-38.

Hamilton,W., (1977). Subduction inthe Indonesian region, in is land arcs, deep sea trenches and back arc basins, Maurice Ewing Ser., (eds Talwani, M. and Pitman, W.C. III, AGU, Washington, D.C.), 1, 15-31.

Kanamori,H., (1977). The energy released in great earthquakes, J. Geophys. Res., 82, 2981-2987.

Karig,D.E., (1973). Plate convergence between the Philippines and the Ryukyu Islands, Mar. Geol., 14,153-168.

Lee,T.Q., Liaw,J.S. and Tsai,Y.B., (1978a). Further evidence for subduction of the Philippine Sea Plate underneath northern Taiwan, Proc. Geol. Soc. China, 21, 168-175.

Lee,W.H.K., Wu,F.T. and Wang,S.C., (1978b). A catalog of instrumentally determined earthquakes in China (Magnitudes$\geq$6) compiled from various sources, Bull. Seism. Soc. Am., 68, 383-398.

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.

McCann,W.R., Nishenko,S.P., Sykes,L.R. and Krause,J., (1979). Seismic gaps and plate tectonics: Seismic potential for major boundaries, Pageoph, 117, 1082-1147.

McGuire,R., (1978). Seismic ground motion parameter relation, Proc. ASCE J. Geotech. Eng. Div., 104, 481-490.

Molnar,P., (1979). Earthquake recurrence intervals and plate tectonics, Bull. Seism. Soc. Am., 69, 115-133.

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.C., (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, 1-10.

Papazachos,B.C., (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 and 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, (in press).

Papazachos,B.C. and Papaioannou,Ch.A., (1993). Long-term earthquake prediction in the Aegean area based on a time and magnitude predictable model, Public. Geophys. Lab. Univ. Thessaloniki, 4, 10pp.

Pelletier,B. and Stephan,J.F., (1986). Middle Miocene obduction and Late Miocene beginning of collision registered in the Hengchun Peninsula: Geodynamics implications for the evolution of Taiwan, Tectonophysics, 125, 133-160.

Rikitake,T., (1976). Recurrence of great earthquakes at subduction zones, Tectonophysics, 35, 335-362.

Rowlett,H. and Kelleher,J., (1976). Evolving seismic pattern along the western margin of the Philippines Sea Plate, J. Geophys. Res., 81, 3518-3524.

Shimazaki,K. and Nakata,T., (1980). Time-predictable recurrence model for large earthquake, Geophys. Res. Lett., 7, 279-282.

Tsapanos,T.M., Scordilis,E.M. and Papazachos,B.C., (1990). A global catalogue of strong earthquakes, Publ. Geophys. Lab. Univ. Thessaloniki, 9, 90pp.

Valenzuela,R.G. and Garcia,L.C., (1988). Studies of Philippine historical earthquakes,"Historical Seismograms and Earthquakes of the World", (eds Lee, W.H.K., Meyers, H. and Shimazaki, K.), Academic Press, INC., 289-296.

Weisberg,S., (1980). Applied linear regression, Wiley New York, 283pp.

Wesnousky,S.G., Scholz,C.H., Shimazaki,K. and Matsuda,T.,(1984). Integration of geological and seismological data for analysis od Seismic Hazard: A case study of Japan, Bull. Seism. Soc. Am., 74, 687-708.

York,J.E., (1976). Quaternary faulting in Eastern Taiwan, Bull. Geol. Surv. Taiwan, 25, 63-72.