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# LONG TERM EARTHQUAKE PREDICTION IN CENTRAL AMERICA AND CARIBBEAN SEA BASED ON THE TIME AND MAGNITUDE PREDICTABLE MODEL

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## ABSTRACT

Instrumental and historical information on strong mainshocks for 12 seismogenic sources in Central America and Caribbean Sea 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:

$$LogT_t = 0.30M_{min}+0.48M_p-0.69logM_o+13.70$$

$$M_f = 0.98M_{min}-0.31M_p+0.28logM_o-4.55$$

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. The highest probability ($P_{10}$=0.67) was estimated for the seismogenic source of El Salvador ($A_1$) for the occurrence of a large earthquake with expected magnitude $M_f$=7.5 and high probabilities (P10≥0.55) were estimated for the seismogenic sources of Jamaika ($C_3$) and Puerto Rico ($C_5$) for earthquakes with expected magnitudes $M_f$=7.5 in both sources.

## ΣΥΝΟΨΗ

Η περιοχή της Καραϊβικής και της κεντρικής Αμερικής χωρίστηκε σε 12 σεισμικές πηγές. Από τα δεδομένα των κυρίων σεισμών που έγιναν στις πηγές αυτές, προέκυψαν οι παρακάτω σχέσεις που αφορούν το μέγεθος του αναμενόμενου σεισμού, $M_f$ και του χρονικού διαστήματος μεταξύ 2 κύριων σεισμών $T_t$.

$$LogT_t = 0.30M_{min}+0.48M_p-0.69logM_o+13.70$$

$$M_f = 0.98M_{min}-0.31M_p+0.28logM_o-4.55$$

όπου $M_{min}$ είναι το μέγεθος του μικρότερου κύριου σεισμού που θεωρείται $M_p$ είναι το μέγεθος του προηγούμενου κύριου σεισμού και $M_o$ είναι η ετήσια έκλυση σεισμικής ροής σε κάθε σεισμική πηγή. Με βάση τις σχέσεις αυτές, υπολογίζονται οι πιθανότητες γένεσης ισχυρών σεισμών στη δεκαετία 1993-2002 σε κάθε μία από τις σεισμικές πηγές.

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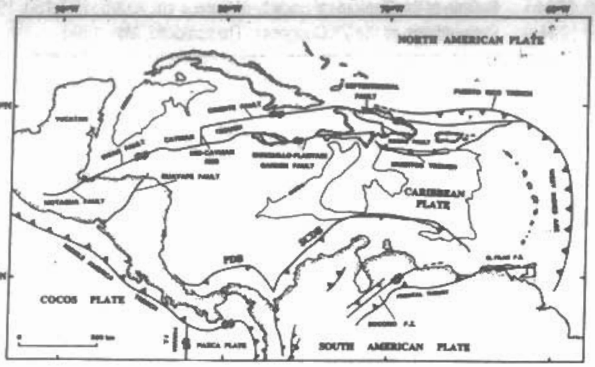


**Fig. 1**: The studied area with the main tectonic features (PDB: Panama Deformed Belt; SCDB: South Caribbean Deformed Belt; modified from Heubeck and Mann, 1991; Jordan, 1975 and Adamek and Frohlich, 1988). The isobath line is the 4000m depth from Case and Holcombe (1980).

## INTRODUCTION

Repeat times of strong earthquakes which occur on single faults are well interpreted by the time predictable model (Bufe et al., 1977; Shimazaki and Nakata, 1980; Sykes and Quitmeyer, 1981; Wesnousky et al., 1984; Astiz and Kanamori, 1984; Nishenko and Buland, 1987). According to this model, the time of occurrence of a future earthquake in a fault depends on the size of the last earthquake in this fault. 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).

Recently, Papazachos (1992) concluded that the time-predictable model as well as the magnitude predictable model hold for the strong shallow earthquakes which occurred in seismogenic sources in the Aegean area. He proposed two formulas where the interevent time, as well as the magnitude of the following mainshock were related to the magnitude of the smallest mainshock considered and to the magnitude of the preceding mainshock in each seismogenic source. Very recently, Papazachos and Papaioannou (1993) improved this idea, by including a new term, in both of these formulas, which depends on the yearly moment rate, $\dot{M}_o$, in each seismogenic source. This is called the "time and magnitude predictable model". They applied this model to estimate the probability of occurrence of the next mainshock during the next decade and the magnitude of this shock for each seismogenic source in the Aegean area. This model has been also tested succesfully in other areas (Papadimitriou, 1993a, b; Papazachos et al., 1993; Tsapanos and Papazachos, 1993).

In the present study an attempt is made to test the applicability of the time and magnitude predictable model in the seismic zones of the Central America and Caribbean Sea (Fig. 1) with data from shallow earthquakes.

The areas of Caribbean Sea and Central America form a small lithospheric plate inserted between the lithospheric plates of North America, South America, Nazca and Cocos (Sykes and Ewing, 1965; Molnar and Sykes, 1969; Stover, 1973). Its northern boundary is formed by a left-lateral transcurrent fault system connected around its eastern end to the subduction zone of Atlantic oceanic lithosphere under Lesser Antilles (Jordan, 1975; Heubeck and Mann, 1991; Calais et al., 1992). McCann and Sykes (1984) suggested that the transition between strike-slip and subduction zone is around 71°W. Calais et al. (1992) suggested that the stress and strain distribution along the northern Caribbean plate boundary exhibit a small N-S convergence component associated with the major eastward strike-slip motion of the Caribbean plate related to North America.

At the western part of the Caribbean plate, the Cocos plate is subducting below the Middle America volcanic arc at the Middle America Trench. This active subduction zone changes to a largely transform boundary near the border of Panama-Costa Rica at the Cocos-Nazca-Caribbean triple junction near the Panama Fracture Zone (Stover, 1973; Adamek et al., 1988; Case and Holcombe, 1980). On the other hand the triple junction of the North America, Cocos and Caribbean plates is ambigously defined because the North America-Caribbean plate boundary does not clearly meet (Motagua fault) the Middle America Trench in western Guatemala (Guzman-Speziale et al., 1989). It is suggested that a broad zone of the deformation in southern Mexico and northern Central America takes up the interaction of the three plates.

The subduction of the Atlantic oceanic lithosphere under the Caribbean plate below the West Indies arc terminates near the northeastern part of Venezuela (Jordan, 1975) and forms the eastern boundary of the Caribbean plate. This is an extreme case of an old subduction (~100 m.y.) at a very slow convergence rate about 2 cm/yr (Jordan, 1975; Stein et al., 1982). This Island arc has experienced a complex history and has probably been active since the Early Cretaceous (Bouysse, 1988; Bouysse and Westercamp, 1990). One particular problem concerns the location and the nature of the Caribbean-North America-South America triple junction because there is no evidence in the shallow seismicity for this "hypothetical" triple junction (Jordan, 1975; Stein et al., 1982).

Finally the southern end of the Caribbean plate north of Panama and South America is along the Panama Deformed Belt (PDB) and South Caribbean Deformed Belt (SCDB) in Figure 1. The nature of these belts is more complex. Bowin (1976) used gravity data to suggest that the boundary of Caribbean and Nazca plates is located along the Panama Deformed Belt (PDB) where Panama, or an individual "Panama Block", overthrusts the Caribbean plate in a northward direction. Recently Wolters (1986) proposes that the PDB zone is a subduction zone, while Lu and McMillen (1982) and Bowland (1984) had shown by multichannel studies that PDB is an overthrust boundary as suggested by Bowin (1976). Although PDB is a convergent plate boundary the absence of intermediate depth earthquakes below 70 km reinforce the aspect that the lithosphere does not subduct beneath this depth (Adamek et al., 1988).

According to Lay and Kanamori (1981) the studied area of Central America is grouped in the category "2-3" of the subduction zones which have characterized by the absence of great mainshocks and small rupture dimensions, but with stronger tendency for events to cluster in space and time.

**METHOD**

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

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

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

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 $M_o$ the moment rate in each source per year. 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 $M_o$ for a seismogenic source can be reliably calculated if enough data are available for the source. In the present study the values of

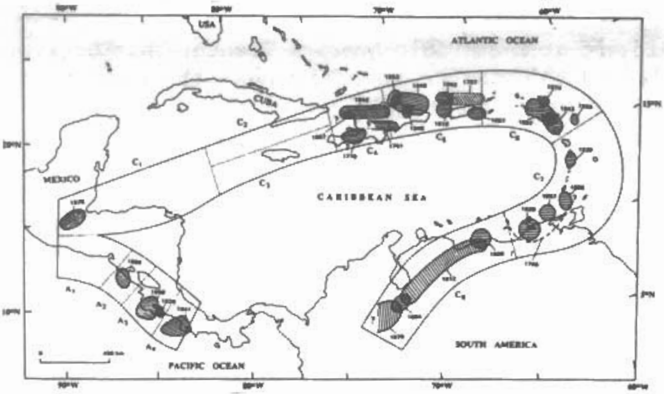


**Fig. 2**: Estimated rupture zones in the area under study since 1700. The rupture zones for the earthquakes of 1939, 1941, 1943, 1946, 1948, 1950, 1953, 1956, 1969, 1974 and 1976 based on aftershocks data while the other estimates are based on isoseismal areas with intensities equal to or greater than 9 (modified from Kelleher et al., 1973; Langer and Bollinger, 1979 and McCann and Sykes, 1984).

the moment rate, $M_0$, were determined 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:

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

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

$$\mathrm{Log}M_0 = rM + k \quad (4)$$

which for the studied area have been taken as r=1.5 and k=16.1 (Kanamori, 1977). On the basis of a well known technique (Draper and Smith, 1966; Weisberg, 1980) which has been used in strong motion attenuation studies (McGuire, 1978; Joyner and Boore, 1981; Dahle et al., 1990) the coefficients of b, c, d and t of the relation 1, as well as the corresponding coefficients of the relation 2 were calculated by the use of all the data of the 12 seismogenic sources (using a computer program written by C. Papazachos).

**SEISMOGENIC SOURCES AND DATA**

A basic step for this work was to define the seismogenic sources of the shallow earthquakes in the area under study. Twelve seismogenic sources were finally defined in the area on the basis of tectonic features (Fig. 1), ruptures zones (Fig. 2) and clustering of epicenters of mainshocks (Fig. 3). Previous recent works concerning the separation of the area for similar purpose, was made by McCann et al. (1979) and Nishenko (1991). Although in many cases the separation made by the aforementioned authors resembles that followed in the present study, there are also some differences.

Along the tectonic line of the Middle America Trench in Central America (between 83°W to 91°W) which is the part of the collision's boundary between the plates Cocos and Caribbean, four seismogenic sources (sources $A_1$, $A_2$, $A_3$ and $A_4$ in Fig.3) were defined. The first seismogenic source, $A_1$, was defined according to the spatial distribution of the two clusters of strong and large earthquakes (Fig. 3) and to the fact that it has not experienced shallow earthquakes with magnitudes $M_s \geq 7.0$ for the last 47 years (Fig. 2). For the same reason Kelleher et al. (1973) suggested this seismogenic source as one of the six gaps along Western Mexico and Central America. The next three seismogenic sources ($A_2$, $A_3$ and $A_4$ in Fig. 3) were defined according to spatial distribution of the large mainshocks and to the fact that the seismogenic source $A_2$ includes the aftershock area of the 1956 earthquake, the seismogenic source $A_3$ includes the aftershock areas of the great 1950 earthquake and of the large 1939 earthquake and the seismogenic source $A_4$ includes the ruptures zone of the large 1941

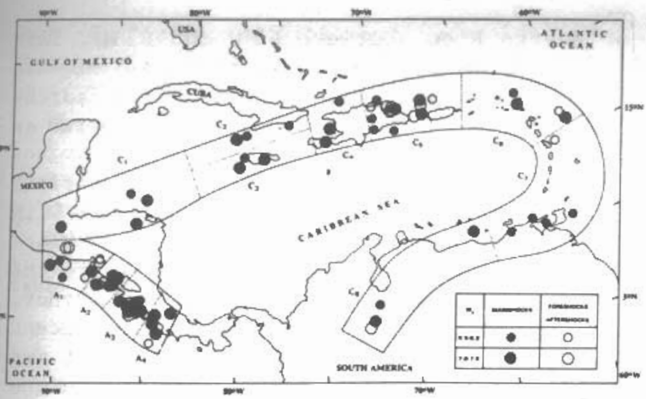


**Fig. 3:** The seismogenic sources in which the area of Central America and Caribbean Sea was divided along with the epicentres of shallow mainshocks (black circles) and fore- or aftershocks (open circles) in their broad sense in the range of the completness.

earthquake (Kelleher et al., 1973; McCann et al., 1979) (Fig. 2).

The system of the Motagua and Swan Fracture Zone (Fig. 1) is a left lateral strike-slip mega-fault (Jordan, 1975; Langer and Bollinger, 1979; Young et al., 1989; Heubeck and Mann, 1991; White and Harlow, 1993). It is the western part of the boundary between the plates of North American and Caribbean from the North America-Cocos-Caribbean triple junction to the Mid-Cayman Rise at the Cayman Trough. McCann et al. (1979) and Nishenko and McCann (1981) suggested that this big area has incomplete historic records and may has potential for large earthquake. On this basis and the spatial distribution of the large earthquakes and the aftershock area of the 1976 Motagua large earthquake, this area was considered as one seismogenic source (source $C_1$ in Fig. 2,3).

At the central part of the boundary between the plates of North American and Caribbean, two left-lateral strike-slip faults form a possible microplate (Fig. 1) from Mid-Cayman Rise to Hispaniola (Jordan, 1975; Heubeck and Mann, 1991; Calais et al., 1992). The northern strike-slip fault is the Oriente Fault south of Cuba and the southern one is the Enriquillo-Plantain Garden Fault through the Jamaika Island. McCann et al. (1979) and Nishenko and McCann (1981) suggested that the Oriente Fault belongs to the category "1" which represents the areas with the highest seismic potential. On the other hand the Enriquillo-Plantain Garden Fault belongs to the category "2" which characterizes regions experienced at least one large earthquake in the past with the most recent event occurring between 1879 and 1949, more than 30 years ago, but less than 100 years ago. According to this and the spatial distribution of the large earthquakes (Fig. 3) the Oriente Fault zone and the Enriquillo-Plantain Garden Fault zone were considered as two seismogenic sources ($C_2$ and $C_3$ at Fig. 2,3).

At the western part of Hispaniola Island (Haiti), Kelleher et al. (1973) have located four rupture zones for four historical strong and large earthquakes (1751, 1770, 1842 and 1887 in Fig. 2) on the basis of isoseismal areas with intensities 9 or greater. According to this and the clustering of the large earthquakes in western Hispaniola this region was considered as a seismogenic source ($C_4$ in Fig. 2,3).

The main tectonic feature at the regions of eastern Hispaniola and Puerto Rico is the Septentrional Fault (Fig. 1). Along this tectonic lineament Kelleher et al. (1973) and McCann and Sykes (1984) have located four rupture zones for four large and great earthquakes (1943, 1946, 1948 and 1953 in Fig. 2) on the basis of aftershock data and three other rupture zones for historical events (1787, 1867 and 1918 in Fig. 2) on the basis of isoseismal areas with intensities 9 or greater. Although there is an ambiguity on the great 1787 earthquake, McCann and Sykes (1984) reported that this shock may have ruptured an existing seismic gap north of Puerto Rico (between 65°W and 67°W). This possible rupture zone was taken into account in our separation of the seismogenic sources. According to these and the clustering of the large and great earthquakes the eastern Hispaniola (Dominikan) and Puerto Rico was considered as a seismogenic source ($C_5$ in Fig. 2,3).

McCann and Sykes (1984) reported that the maximum size of historical shallow earthquakes along the Lesser Antilles arc varies from 7.0-7.5 in the center of the arc where the dip of the shallow part of the plate boundary is steep to 8.0-8.5 along the northern part of the arc where the dip is shallow. At the northern part of this arc the aforementioned authors and Kelleher et al. (1973) have located the rupture zones of two recent large earthquakes (1969 and 1974 in Fig. 2) and the rupture zones of two historical great earthquakes (1843 and 1897 in Fig. 2). The rupture zone of the historical great earthquake of 1843 is in good agreement with the isoseismal areas with intensities VIII or greater (Bernard and Lambert 1988). In the central and southern part of the Lesser Antillean arc and in the region of El Pilar Fracture Zone in northern Venezuela, Kelleher et al. (1973) has located the rupture zones of two strong earthquakes (1929 and 1957 in Fig. 2) and three historical great and large eartquakes (1766, 1839 and 1888 in Fig. 2). On this basis and the spatial distribution of the large earthquakes along the Lesser Antillean arc and the El Pilar Fracture Zone, and taking into account the zonation of McCann et al. (1979) and Nishenko and McCann (1981), the Lesser Antillean arc was considered as two seismogenic sources ($C_6$ and $C_7$ in Fig. 2,3)

Finally, Kelleher et al. (1973) has located the rupture zones for four historical large and great earthquakes (1812, 1875, 1894 and 1900 in Fig. 2) along the Bocono Fracture Zone in Venezuela. According to that and the spatial distribution of the large earthquakes at the Bocono Fracture Zone this region was considered as the last seismogenic source ($C_8$ in Fig. 2,3) in this study.

These twelve seismogenic sources are shown in Fig. 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 foreshocks and aftershocks in the broad sense, that is, earthquakes which may occur up to several years before or after the main shock, respectively.

The terms "foreshocks" and "aftershocks" are used in their broad sense, because a model is required 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 there have been considered the eartquakes which had preceded the mainshocks in a time period of 3 years (Karakaisis et al., 1991). As aftershocks there have been considered the eartquakes which had followed the mainshocks in a time period of $T_1$ (years). This time period, $T_1$, is related to the magnitude, $M_s$, of the mainshock by the relation:

$$\mathbf{Log(T_1) = 0.06 + 0.13M_s} \qquad (5)$$

which have been derived by the use of a very lerge sample of data (B.C. Papazachos, 1993, *personal communication*).

Information on the magnitudes and on the epicenters of the earthquakes plotted in Fig. 3, were taken 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 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), Abe (1984), Russo et al. (1992), Kelleher et al. (1973), Tsapanos et al. (1990) and the monthly bulletins of ISC and USCGS.

The values of the parameters b, a, $M_{max}$ and the $logM_o$, for each seismogenic source are listed in Table 1. The name and the number for the seismogenic sources, corresponding to the sources in Figure 3, are listed in the first two columns of this table.

Table 2 lists all the information on the data used in the present study.

**Table 1.** Basic parameters which are used for every source. The code number and the names of the sources are given in the first and second columns. The constants for the Gutenberg-Richter relation are given in the next two columns and the maximum magnitude and the logarithm of the moment rate are given in the last two columns.

| Seismogenic sources | a | b | $M_{max}$ | $LogM_o$ |
|---|---|---|---|---|
| Source A1 EL SALVADOR | 6.43 | 1.14 | 7.2 | 25.74 |
| Source A2 NICARAGUA | 6.34 | 1.14 | 7.2 | 25.65 |
| Source A3 COSTA RICA | 6.56 | 1.14 | 7.7 | 26.05 |
| Source A4 COSTA RICA (SAN JOSE) | 6.39 | 1.14 | 7.6 | 25.85 |
| Source C1 MOTAGUA-SWAN F.Z. | 6.25 | 1.14 | 7.5 | 25.67 |
| Source C2 SW CUBA | 5.90 | 1.14 | 7.1 | 25.18 |
| Source C3 JAMAIKA | 6.22 | 1.14 | 7.3 | 25.57 |
| Source C4 HISPANIOLA (HAITI) | 6.27 | 1.14 | 7.0 | 25.80 |
| Source C5 PUERTO-RICO | 6.71 | 1.14 | 7.8 | 26.13 |
| Source C6 GUADELOUPE | 6.07 | 1.14 | 7.3 | 25.42 |
| Source C7 TOBAGO TROUGH-TRINIDAD | 6.13 | 1.14 | 7.0 | 25.37 |
| Source C8 BOCONO F.Z. | 6.32 | 1.14 | 7.6 | 25.78 |

A name is written for each seismogenic source in the first column of this table. The second column shows the time (year) during which the data are complete for each magnitude range and the minimum magnitude range, respectively. The date, epicenter and the surface wave magnitude for each shock which satisfy the completeness condition defined in the second column, are given at the third, fourth and fifth columns of this table. The sixth column shows the cumulative magnitude, M, of each sequence, that is, the

**Table 2**: Basic information on the data used for each seismogenic source (f:foreshocks, a:aftershocks in their broad sense).

| Seismogenic Source | Completeness | | Date | | | Epicenter | | Ms | M | Ref |
|---|---|---|---|---|---|---|---|---|---|---|
| SOURCE A1 | 1940, | 6.5 | 9 | 11 | 1900 | 13.0 | -90.0 | 7.0 | 7.2 | 3 |
| EL SALVADOR | 1897, | 7.0 | 8 | 10 | 1901 | 13.0 | -87.0 | 7.0 | a | 1 |
| | | | 28 | 3 | 1921 | 12.5 | -87.5 | 7.2 | 7.5 | 1 |
| | | | 1 | 5 | 1924 | 14.0 | -89.0 | 7.0 | a | 8 |
| | | | 8 | 2 | 1926 | 13.0 | -89.0 | 7.0 | a | 1 |
| | | | 14 | 7 | 1930 | 14.0 | -89.0 | 7.0 | a | 8 |
| | | | 7 | 10 | 1945 | 12.2 | -89.2 | 6.7 | 7.0 | 8 |
| | | | 3 | 8 | 1951 | 13.0 | -87.0 | 6.7 | a | 8 |
| | | | 20 | 11 | 1952 | 12.1 | -87.9 | 6.7 | a | 8 |
| | | | 26 | 4 | 1955 | 13.2 | -89.4 | 6.5 | 6.5 | 8 |
| SOURCE A2 | 1940, | 6.5 | 29 | 4 | 1898 | 12.0 | -86.0 | 7.0 | 7.0 | 3 |

| Seismogenic Source | Completeness | | Date | | | Epicenter | | Ms | M | Ref |
|---|---|---|---|---|---|---|---|---|---|---|
| NICARAGUA | 1897, | 7.0 | 30 | 12 | 1907 | 12.1 | -86.3 | 7.1 | 7.1 | 1 |
| | | | 26 | 2 | 1952 | 11.5 | -86.3 | 6.7 | 6.7 | 8 |
| | | | 19 | 2 | 1954 | 11.7 | -86.9 | 6.8 | f | 8 |
| | | | 19 | 2 | 1954 | 11.9 | -86.8 | 6.5 | f | 8 |
| | | | 24 | 10 | 1956 | 11.5 | -86.5 | 7.2 | 7.3 | 1 |
| | | | 2 | 9 | 1992 | 11.7 | -87.3 | 7.2 | 7.2 | 6 |
| SOURCEA3 | 1940, | 6.5 | 21 | 6 | 1900 | 10.0 | -85.5 | 7.1 | 7.1 | 1 |
| COSTARICA | 1897, | 7.0 | 27 | 2 | 1916 | 10.7 | -86.0 | 7.3 | 7.4 | 1 |
| | | | 26 | 4 | 1916 | 10.0 | -85.0 | 7.1 | a | 2 |
| | | | 21 | 12 | 1939 | 10.0 | -85.0 | 7.1 | 7.2 | 1 |
| | | | 27 | 10 | 1940 | 9.7 | -84.5 | 6.7 | a | 8 |
| | | | 5 | 10 | 1950 | 10.4 | -85.0 | 7.7 | 7.7 | 1 |
| | | | 13 | 5 | 1952 | 10.3 | -85.3 | 7.0 | a | 8 |
| | | | 14 | 4 | 1973 | 10.6 | -84.9 | 6.5 | 6.5 | 6 |
| | | | 23 | 8 | 1978 | 10.2 | -85.3 | 7.0 | 7.0 | 6 |
| | | | 25 | 3 | 1990 | 10.0 | -84.8 | 7.0 | 7.0 | 6 |
| SOURCEA4 | 1940, | 6.5 | 4 | 3 | 1924 | 9.7 | -84.0 | 7.0 | 7.0 | 2 |
| COSTARICA | 1897, | 7.0 | 6 | 12 | 1941 | 8.5 | -84.0 | 7.0 | 7.0 | 2 |
| (SANJOSE) | | | 9 | 9 | 1952 | 9.2 | -84.2 | 7.2 | 7.2 | 8 |
| | | | 6 | 6 | 1958 | 7.9 | -84.5 | 6.6 | a | 8 |
| | | | 22 | 4 | 1991 | 9.7 | -83.1 | 7.6 | 7.6 | 6 |
| SOURCEC1 | 1940, | 6.5 | 1 | 1 | 1910 | 16.5 | -84.0 | 7.0 | 7.0 | 1 |
| MOTAGUAF.Z. | 1897, | 7.0 | 28 | 5 | 1914 | 15.1 | -84.8 | 7.5 | 7.5 | 8 |
| SWANF.Z. | | | 27 | 6 | 1948 | 17.0 | -85.0 | 6.7 | 6.7 | 8 |
| | | | 4 | 2 | 1976 | 15.3 | -89.2 | 7.5 | 7.5 | 1 |
| SOURCEC2 | 1940, | 6.5 | 20 | 2 | 1917 | 19.5 | -78.5 | 7.1 | 7.1 | 1 |
| SWCUBA | 1897, | 7.0 | 7 | 8 | 1947 | 19.7 | -75.2 | 6.7 | 6.7 | 8 |
| | | | 25 | 5 | 1992 | 19.6 | -77.9 | 6.9 | 6.9 | 6 |
| SOURCEC3 | 1940, | 6.5 | 14 | 6 | 1899 | 18.0 | -77.0 | 7.3 | 7.3 | 3 |
| JAMAIKA | 1897, | 7.0 | 7 | 4 | 1941 | 17.7 | -78.5 | 7.0 | 7.0 | 2 |
| | | | 2 | 3 | 1957 | 18.3 | -78.1 | 6.5 | 6.5 | 8 |
| SOURCEC4 | 1940, | 6.5 | 29 | 12 | 1897 | 19.0 | -73.0 | 7.0 | 7.0 | 3 |
| HISPANIOLA | 1897, | 7.0 | 28 | 10 | 1952 | 18.3 | -73.3 | 7.0 | 7.0 | 8 |
| (HAITI) | | | 20 | 4 | 1962 | 20.5 | -72.1 | 6.7 | 6.7 | 8 |
| SOURCEC5 | 1940, | 6.5 | 17 | 2 | 1902 | 20.0 | -70.0 | 6.9 | 6.9 | 3 |
| PUERTORICO | 1897, | 7.0 | 6 | 10 | 1911 | 19.0 | -70.5 | 6.9 | 6.9 | 2 |
| | | | 27 | 7 | 1917 | 19.0 | -67.5 | 7.0 | f | 2 |
| | | | 11 | 10 | 1918 | 18.5 | -67.5 | 7.3 | 7.5 | 1 |
| | | | 25 | 10 | 1918 | 18.5 | -68.0 | 7.0 | a | 8 |
| | | | 29 | 7 | 1943 | 19.2 | -67.5 | 7.5 | 7.5 | 1 |
| | | | 30 | 7 | 1943 | 19.2 | -66.8 | 6.5 | a | 9 |
| | | | 4 | 8 | 1946 | 19.2 | -69.0 | 7.8 | 7.9 | 1 |
| | | | 8 | 8 | 1946 | 19.5 | -69.5 | 7.4 | a | 1 |
| | | | 21 | 8 | 1946 | 19.3 | -69.3 | 7.0 | a | 9 |
| | | | 21 | 4 | 1948 | 19.2 | -69.2 | 7.1 | a | 2 |
| | | | 22 | 4 | 1948 | 19.3 | -69.3 | 7.2 | a | 8 |
| | | | 31 | 5 | 1953 | 19.7 | -70.4 | 6.9 | a | 8 |

| Seismogenic Source | Completeness | | Date | | | Epicenter | | Ms | M | Ref |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 8 | 1 | 1962 | 18.4 | -70.5 | 6.7 | 6.7 | 8 |
| | | | 24 | 6 | 1984 | 18.0 | -69.3 | 6.7 | 6.7 | 6 |
| SOURCEC6 | 1940, | 6.4 | 31 | 5 | 1960 | 18.0 | -62.0 | 6.4 | 6.4 | 8 |
| GUADELOUPE | 1897, | 7.0 | 25 | 12 | 1969 | 15.8 | -59.6 | 7.0 | 7.0 | 1 |
| | | | 25 | 12 | 1969 | 16.1 | -59.8 | 6.5 | a | 6 |
| | | | 8 | 10 | 1974 | 17.4 | -62.0 | 7.3 | 7.3 | 1 |
| SOURCEC7 | 1940, | 6.4 | 17 | 1 | 1929 | 10.4 | -64.0 | 6.9 | 7.0 | 7 |
| TOBAGOTROUGH | 1897, | 7.0 | 23 | 12 | 1945 | 10.2 | -62.0 | 6.5 | 6.7 | 7 |
| TRINIDAD | | | 21 | 5 | 1946 | 14.8 | -60.4 | 6.5 | a | 7 |
| | | | 4 | 10 | 1957 | 10.9 | -62.8 | 6.7 | 6.7 | 7 |
| | | | 10 | 3 | 1988 | 10.2 | -60.5 | 6.4 | 6.4 | 6 |
| SOURCEC8 | 1930, | 6.5 | 29 | 10 | 1900 | 11.0 | -66.0 | 7.6 | 7.6 | 1 |
| BOCONOFAULT | 1897, | 7.0 | 14 | 3 | 1932 | 8.2 | -71.7 | 6.7 | 6.7 | 8 |
| | | | 19 | 4 | 1952 | 7.2 | -72.1 | 7.5 | 7.6 | 8 |
| | | | 21 | 4 | 1957 | 7.0 | -72.3 | 7.1 | a | 8 |

1. Pacheco and Sykes (1992), 2. Abe (1981), 3. Abe and Noguchi (1983), 4. Abe (1984), 5. ISC, 6. USCGS, 7. Russo et al. (1992), 8. Tsapanos et al. (1990), 9. Kelleher et al (1973).

magnitude which corresponds to the total moment released by the major shocks (main shocks and large foreshocks and aftershocks) of each seismic sequence according to the relation suggested by Kanamori (1977). In this study these cumulative magnitudes are used instead of the magnitudes of the mainshocks.

A common value for the parameter b (1.14) was estimated for the area covered by the twelve seismogenic sources in Fig. 3 by applying the least squares method, in all complete data.

**EMPIRICAL RELATION**

The data for the twelve seismogenic sources were used in order to estimate the parameters of the relation 1. It was observed that by excluding some observations (about 10% of the available) which gave very large residuals, a considerable increase of the multiple correlation coefficient occurred. For this reason the remaining (50) observations (T, $M_{min}$, $M_p$, $M_o$) were finally used to determine the relation:

$$\mathrm{Log}T_t = 0.30M_{min} + 0.48M_p - 0.69\log M_o + 13.70 \quad (6)$$

with a correlation coefficient equal to 0.77 and a standard deviation equal to 0.19. The strong positive correlation between the repeat time and the magnitude $M_p$ (c=0.48) indicates that the time-predictable model holds very well. In a similar way the parameters of the relation 2 were determined and the following empirical formula was obtained:

$$M_f = 0.98M_{min} - 0.31M_p + 0.28\log M_o - 4.55 \quad (7)$$

with a correlation coefficient equal to 0.73 and a standard deviation equal to 0.24. The meaning of the strong negative value of C (-0.31) is that large mainshocks are followed by small ones and vice versa.

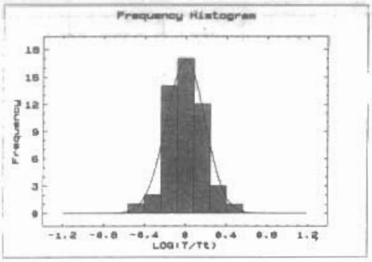


**Fig. 4**: The frequency distribution of the observed repeat times compared to the theoretical one.

## LONG TERM EARTHQUAKE PREDICTON

Papazachos (1988, 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. This is in accordance with a similar study of Nishenko and Buland (1987).

Figure 4 displays the frequency histogram of $Log(T/T_t)$ and the theoretical normal distribution which has a mean equal to zero and standard deviation equal to 0.20. Figure 5 displays the frequency histogram of the difference $(M_F-M_f)$ between the observed magnitude $M_F$ of the following mainshock and the calculated magnitude $M_f$ by the relation 7 and the theoretical normal distribution which has a mean equal to zero and standard deviation equal to 0.24. 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 (1993-2002) for earthquakes with magnitudes equal to or larger than 7.0 were calculated.

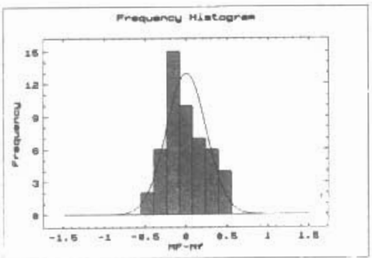


**Fig. 5**: The frequency distribution of the difference $M_F-M_f$ between the observed $M_F$ and the calculated $M_f$ of the following mainshocks by the relation 7.

Table 3 gives information on the expected large ($M_s \geq 7.0$) shallow mainshocks based on the model expressed by the relations 6 and 7. The first two columns give the code number and the name of the seismogenic sources shown in Figures 2,3. The last two columns of this table give the probability values, $P_{10}$ for the occurrence of large ($M_{min} \geq 7.0$) shallow earthquakes during the next decade (1993-2002) with the corresponding magnitudes $M_f$ of the expected mainshocks as these magnitudes were calculated by the relation 7. It is interesting to note that the absolute values of probability are of relative importance because there is a possibility to have changes to these values if a larger sample of data is used.

The seismogenic source of El Salvador ($A_1$), exhibits the highest probability value ($P_{10}$=0.67) among all the seismogenic sources, for the occurrence of a mainshock with $M_s \geq 7.0$. In addition high probability values ($P_{10} \geq 0.55$) for the occurrence of a mainshock with $M_s \geq 7.0$ were calculated for the seismogenic sources of Jamaika ($C_3$) and Puerto Rico ($C_5$). Intermediate probability values ($0.55 > P_{10} \geq 0.40$) were calculated for the seismogenic sources of Costa Rica ($A_3$), Hispaniola-Haiti ($C_4$), Tobago Trough-Trinidad ($C_7$) and Bocono Fracture Zone. ($C_8$). Finally low probability values ($P_{10} < 0.40$) for $M_s \geq 7.0$ were calculated for the seismogenic source of Nicaragua ($A_2$), Costa Rica (San Jose, $A_4$), Motagua-Swan Fracture Zone. ($C_1$), SW Cuba ($C_2$) and Guadeloupe ($C_6$).

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**Table 3**: Information on the expected shallow earthquakes with magnitudes, $M_f$, and the corresponding probabilities, $P_{10}$, for the occurrence of large or great ($M_s \geq 7.0$) one during the period 1993-2002 in the area of Caribbean Sea.

| SEISMOGENIC SOURCE | | | $M_s \geq 7.0$ | |
|---|---|---|---|---|
| | | | $M_f$ | $P_{10}$ |
| SOURCE | A1 | ELSALVADOR | 7.5 | 0.67 |
| SOURCE | A2 | NICARAGUA | 7.3 | 0.01 |
| SOURCE | A3 | COSTA RICA | 7.4 | 0.53 |
| SOURCE | A4 | COSTA RICA (SAN JOSE) | 7.2 | 0.01 |
| SOURCE | C1 | MOTAGUA-SWAN F.Z. | 7.2 | 0.16 |
| SOURCE | C2 | SW CUBA | 7.2 | 0.01 |
| SOURCE | C3 | JAMAIKA | 7.5 | 0.58 |
| SOURCE | C4 | HISPANIOLA (HAITI) | 7.5 | 0.53 |
| SOURCE | C5 | PUERTO RICO | 7.5 | 0.61 |
| SOURCE | C6 | GUADELOUPE | 7.2 | 0.11 |
| SOURCE | C7 | TOBAGO TROUGH-TRINIDAD | 7.4 | 0.50 |
| SOURCE | C8 | BOCONO F.Z. | 7.2 | 0.43 |

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