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A Time- and Magnitude-predictable Model for Generation of Shallow Earthquakes in the Aegean Area

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Abstract—Repeat times of strong shallow mainshocks have been determined by the use of instrumental and historical data for 68 seismogenic sources in the Aegean and surrounding area (34°N–43°N, 18°E–30°E). For 49 of these sources at least two interevent times (three mainshocks) are available for each source. By using the repeat times for these 49 sources the following relation has been determined:

$$\log T_t = 0.36M_{\min} + 0.35M_p + a$$

where T_t is the repeat time, measured in years, M_p the surface wave magnitude of the preceding mainshock, $M_{\min}$ the magnitude of the smallest earthquake considered and "a" parameter which varies from source to source. A multilinear correlation coefficient equal to 0.89 was determined for this relation.

By using the same repeat times for the 49 seismogenic sources, the following relation has been determined between the magnitude, M_f, of the following mainshock and $M_{\min}$ and M_p.

$$M_f = 0.95M_{\min} - 0.49M_p + m$$

where m is a constant which varies from source to source. A multilinear correlation coefficient equal to 0.80 was found for this relation.

The model expressed by these two relations is represented by a scheme of a time variation of stress under constant tectonic loading. In this scheme, the maximum stress values during the different seismic cycles fluctuate around a value, τ_1, in a relatively narrow stress interval, expressing the high correlation coefficient of the relation between Log T and M_p. On the contrary, the minimum stress values fluctuate around a value, τ_2, in a much broader stress interval. However, each of these minimum stress values becomes lower or higher than τ_2 if the previous one is higher or lower than τ_2, respectively, expressing the negative correlation between M_f and M_p.

Key words: Time dependent models, seismogenic source, Aegean area.

Introduction

Most of the earthquake generation models currently used for seismic hazard evaluation assume a Poisson or other memoryless distributions (CORNELL, 1968). However, a temporal dependence between large earthquakes in several regions has

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been recently observed (SHIMAZAKI and NAKATA, 1980; SYKES and QUITTMEYER, 1981; WESNOUSKY *et al.*, 1984; PAPAZACHOS, 1989).

Two kinds of time dependent models have been proposed: the slip-predictable model and the time-predictable model (BUFE *et al.*, 1977; SHIMAZAKI and NAKATA, 1980). According to the first of these models, the size (coseismic slip, seismic moment, magnitude) of a future earthquake in a seismic source depends on the time elapsed since the last earthquake, while according to the second model the time of occurrence of a future earthquake depends on the size and the time of occurrence of the last earthquake in the seismic source. Therefore, we can predict, in principle, only the size of a future earthquake by the slip-predictable model and only the time of its occurrence by the time-predictable model.

The time-dependent models have been applied to investigate shocks on single faults and, in particular, characteristic earthquakes (WESNOUSKY *et al.*, 1984; ASTIZ and KANAMORI, 1984; NISHENKO and BULAND, 1987) or in seismic sources which include, in addition to the main fault where the characteristic earthquake is generated, other smaller faults, where smaller mainshocks also occur (PAPAZACHOS, 1989).

Most of the aforementioned investigations as well as other independent data (MOGI, 1981) favor the time-predictable modes.

Research work on the time dependence between strong earthquakes can be of theoretical interest because it can improve our understanding of the earthquake generation process, as well as of practical importance, because it can contribute to long-term earthquake prediction and to a more accuarate evaluation of seismic hazard (KIREMIDJIAN and ANAGNOS, 1984; ANAGNOS and KIREMIDJIAN, 1984).

For these reasons, the present author, undertook, during the last five years, an investigation to identify time-dependent relations between strong earthquakes which occurred in seismogenic sources of shallow earthquakes in Greece. By the use of instrumental data (of the period 1911–1987), repeat times, T, of the mainshocks (with $M_s > 5.8$) in seven very active seismogenic sources were determined and their logarithms were linearly correlated with the magnitudes, M_p, of the preceding mainshocks as well as with the magnitudes, M_f, of the following mainshocks (PAPAZACHOS, 1988a; PAPAZACHOS, 1989). A strong positive correlation between $\log T$ and M_p, and a weak negative correlation between $\log T$ and M_f were found. Therefore, the time-predictable model holds for these earthquakes and not the slip-predictable model. A relation of the form

$$\log T_t = bM_{\min} + cM_p + a \tag{1}$$

has been determined, for these seven sources, between the repeat time, T_t, the magnitude, M_p, of the preceding mainshock and the magnitude, $M_{\min}$, of the smallest mainshock considered (PAPAZACHOS, 1988b). It was assumed that b and c are the same for all seven seismic sources and the values $b = 0,41$, $c = 0.28$ were determined. By using these values and the available data, a value of the parameter "*a*" was determined for each seismogenic source, since this parameter depends on the seismicity level of the source.

In the present paper, an attempt is made to expand the previous work in time, to include historic earthquakes, and in space, to cover the whole Aegean and surrounding area (34°N–43°N, 18°E–30°E). This area includes Greece, Albania, southern Yugoslavia, southern Bulgaria and western Turkey. Previous results, based on a relatively small sample of data, are confirmed by a very large sample of data used in the present paper and more accurate values for some very important parameters are determined. Furthermore, new results, concerning a relation between the magnitude of the preceding and the following mainshocks, in combination with the relation between the interevent time and the magnitude of the preceding mainshock, lead to a model which permits an estimation of the time and the magnitude of the expected mainshock in each seismogenic source.

This area is, seismically, the most active of all of western Eurasia. For this reason, a satisfactory sample of data for the most active seismogenic sources can be obtained. On the other hand, such studies in an area with a variety of seismotectonic regimes are of particular interest. Thrust type faulting occurs along the southern and western coast of the area, normal faulting occurs in the inner part of the Aegean and surroundings and strike-slip faulting occurs along the northern Anatolia seismic belt and its extension to the northern Aegean (McKenzie, 1978; Papazachos *et al.*, 1991).

The Seismogenic Sources

The Aegean and surrounding area has been separated in seismic zones of shallow earthquakes on the basis of several seismological, geological and geomorphological criteria (Papazachos, 1990). Each of these zones has been separated, for the purposes of the present paper, into seismogenic sources on the basis of similar criteria and mainly on the basis of spatial clustering of the epicenters of strong earthquakes, 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 supplementary criterion for this separation.

Each seismogenic source includes the main seismic fault, where the maximum (characteristic) earthquake occurs, but it can also include other smaller faults where smaller mainshocks may also occur. In this way, the whole area has been separated in 68 seismogenic sources which are shown in Figure 1 together with the epicenters of the complete data used in the present study. Black circles show epicenters of mainshocks. Open circles show epicenters of foreshocks and aftershocks in the broad sense, that is, earthquakes, within the complete sample of data, which may occur up to several years before or after the mainshock, respectively. We use the

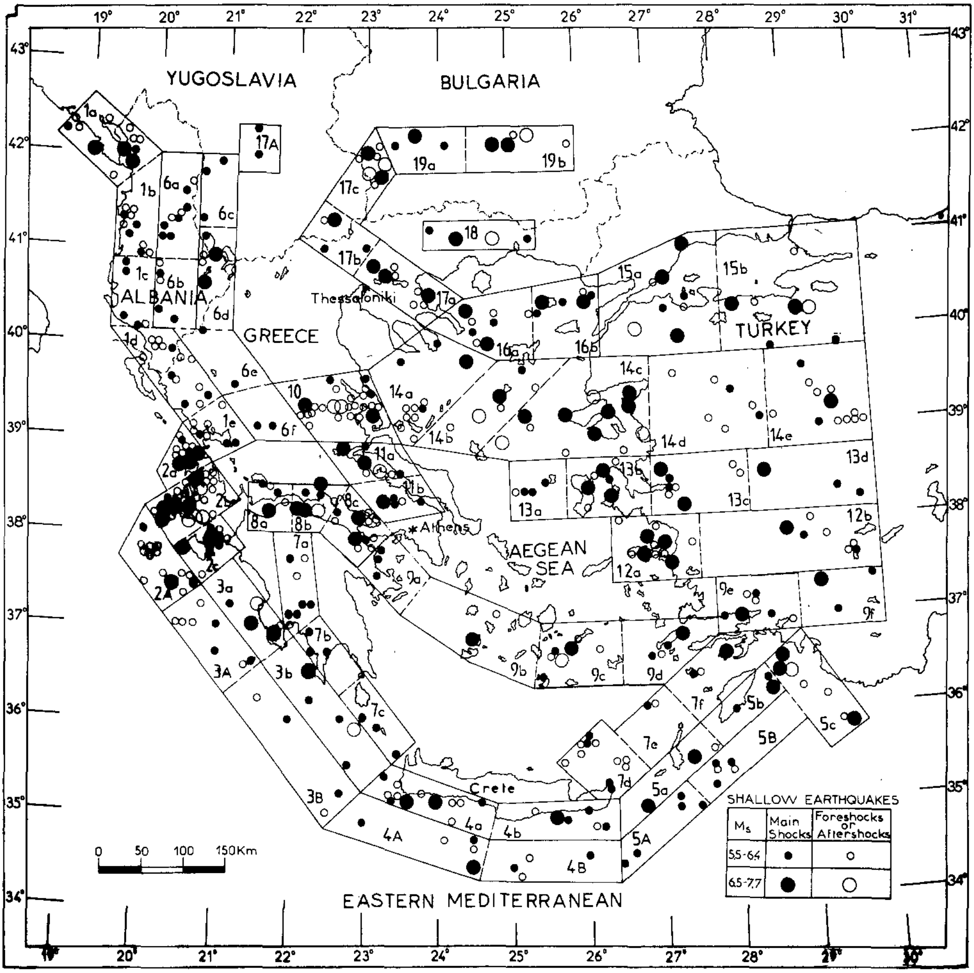

Figure 1
The 68 seismogenic sources of shallow earthquakes in the Aegean and surrounding areas.

terms "aftershock" and "foreshock" in their broad sense because in the present paper we want a model which can predict the mainshocks in each seismogenic source, 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, we consider as foreshocks or aftershocks the earthquakes which precede or follow mainshocks with magnitudes 5.5–5.7, 5.8–6.0, 6.1–7.0, and larger than 7.0 up to 6, 7, 9 and 12.5 yrs, respectively.

Information on the surface wave magnitudes and on the epicenters of the earthquakes plotted in Figure 1 were taken from the catalogue of COMNINAKIS and PAPAZACHOS (1986) for the period 1901–1985 and from the monthly bulletins of the National Observatory of Athens and of the Geophysical Laboratory of the

University of Thessaloniki for the period 1986–1990. For historical earthquakes such information was derived from the book of PAPAZACHOS and PAPAZACHOU (1989).

Information on the data used in the present study is given in Table 1. In the first column of this table a code number, corresponding to the same area numbers of Figure 1, and a name are written for each seismogenic source.

The second column of Table 1 shows the time (year) during which the data are complete for each magnitude range and the minimum magnitude of this range, respectively. For the first source, for example, the complete samples are: all earthquakes with $M_s \geq 6.5$ which occurred in the period 1855–1990 and all earthquakes with $M_s \geq 5.5$ which occurred in the period 1905–1990. This completeness has been determined for each source on the basis of information given in the catalogues, which have been used as data sources, and of plots of the frequency–magnitude relation for each magnitude range.

The third, fourth and fifth columns of Table 1 give the date, epicenter (North latitude, East longitude) and the surface wave magnitude for the mainshocks which satisfy the completeness condition defined in the second column.

The sixth column gives the cumulative magnitude, M, of each sequence, that is, the magnitude which corresponds to the total moment released by the major shocks (main shock and large foreshocks and aftershocks) of each sequence according to a relation between surface wave magnitude and seismic moment which holds for earthquakes in this area (PAPAZACHOS and PAPAZACHOU, 1989). These cumulative magnitudes were used in this study instead of the magnitudes of the mainshocks, although the differences are small.

Data Used to Determine the Parameters of the Empirical Formulae

Table 2 gives the values of the minimum magnitude, $M_{\min}$, of the mainshock, the magnitude of the preceding mainshock, M_p, the magnitude of the following mainshock, M_f, the year of occurrence of the preceding mainshock, t_p, the year of occurrence of the following mainshock, t_f, and the interevent (repeat) time, T, between the two shocks, as these values were derived from the basic data of Table 1 for each seismogenic source.

To understand the way in which these values were derived from Table 1, we will explain this procedure for the first source of this table (source 1a). There are two complete samples for this zone (see the completeness column of Table 1). The one sample includes all mainshocks with $M \geq 5.5$ which occurred between 1905 and 1990 in this source, and the other sample includes all mainshocks with $M \geq 6.5$ which occurred between 1855 and 1990.

We start with the first sample (the sample of the most recent shocks), that is, with the four mainshocks of the period 1905–1990. The smallest earthquake in this

Table 1

Information on the basic data used for each seismogenic source

Source	Completeness	Date	Epicenter	M_s	M
1a	1855, 6.5	03:07:1855	41.9,19.6	6.5	6.5
M. Negro	1905, 5.5	01:06:1905	42.0,19.5	6.6	6.6
		27:08:1948	42.0,19.5	5.6	5.6
		20:08:1966	42.2,18.6	5.7	5.7
		15:04:1979	42.0,19.0	7.1	7.1
1b	1869, 6.2	28:09:1870	41.1,19.6	6.4	6.5
Dirrachio	1920, 5.5	17:12:1926	41.3,19.5	6.1	6.2
		01:09:1959	40.9,19.8	6.4	6.5
		09:01:1988	41.2,19.7	5.6	5.6
1c	1893, 6.2	14:07:1893	40.1,19.8	6.4	6.5
Avlona	1917, 5.7	21:11:1930	40.2,19.6	6.3	6.3
		18:03:1962	40.7,19.6	6.0	6.0
		16:11:1982	40.8,19.6	5.7	5.7
1d	1917, 5.5	21:10:1920	39.6,20.3	5.8	6.1
Igumenitsa		09:02:1967	39.9,20.3	5.8	6.0
		10:03:1981	39.4,20.8	5.6	6.0
		16:06:1990	39.2,20.5	5.5	5.5
1e	1891, 5.5	27:06:1891	39.0,20.7	6.0	6.0
Preveza		13:09:1921	38.9,21.2	6.0	6.2
		29:10:1966	38.9,21.1	6.0	6.2
2a	1825, 6.3	19:01:1825	38.7,20.6	6.7	6.7
Leukada	1911, 5.5	28:12:1869	38.8,20.7	6.6	6.6
		27:11:1914	38.8,20.6	6.3	6.4
		13:03:1938	38.8,20.6	5.8	5.9
		22:04:1948	38.7,20.5	6.5	6.8
		04:11:1973	38.9,20.5	5.8	5.9
2b	1767, 7.2	22:07:1767	38.2,20.3	7.2	7.2
Cephalonia	1862, 6.3	04:02:1867	38.2,20.4	7.2	7.2
	1912, 5.7	24:01:1912	38.1,20.8	6.8	7.2
		12:08:1953	38.2,20.6	7.2	7.4
		17:09:1972	38.3,20.3	6.3	6.3
		17:01:1983	38.1,20.2	7.0	7.0
2c	1840, 6.0	30:10:1840	37.9,20.9	6.7	6.7
Zakynthos	1911, 5.8	25:10:1873	37.9,21.0	6.1	6.1
		17:04:1893	37.9,20.9	6.4	6.4
		20:09:1939	38.0,20.5	6.3	6.3
		15:11:1959	37.8,20.5	6.8	6.9
		16:10:1988	37.9,21.0	6.0	6.0
2A	1938, 5.5	14:02:1943	38.0,20.0	5.8	6.0
Ionian Sea 1		27:08:1958	37.4,20.7	6.4	6.6
		11:05:1976	37.4,20.4	6.5	6.6
3a	1885, 6.1	27:08:1886	37.0,21.5	7.5	7.5
Pylos	1911, 5.9	06:10:1947	36.9,21.8	7.0	7.0
		20:08:1989	37.2,21.2	5.9	5.9

Table 1 (*Contd*)

Source	Completeness	Date	Epicenter	M_s	M
3b	1866, 6.8	20:09:1867	36.5,22.3	7.1	7.2
Mani	1925, 5.5	30:09:1932	36.0,22.7	5.6	5.6
		31:08:1951	35.5,22.8	5.6	5.6
		02:01:1958	36.2,22.3	5.7	5.7
3A	1919, 5.5	24:02:1919	36.7,21.0	6.3	6.4
Ionian Sea 2		01:06:1947	36.6,21.5	5.8	6.0
		16:12:1963	37.0,21.0	5.9	6.0
3B	1922, 5.7	19:09:1926	36.0,22.0	6.3	6.4
Ionian Sea 3		26:01:1962	35.2,22.7	6.2	6.3
4a	1805, 7.2	03:07:1805	35.1,24.0	7.2	7.2
SW Crete	1916, 5.6	30:08:1947	35.1,23.4	6.3	6.4
		14:05:1959	35.1,24.6	6.3	6.3
		04:05:1972	35.1,23.6	6.5	6.6
		21:06:1984	35.4,23.3	6.2	6.2
4b	1815, 6.7	00:12:1815	34.9,25.6	6.7	6.7
SE Crete	1927, 5.6	24:03:1927	35.0,26.0	5.6	5.6
		10:02:1938	34.8,26.2	5.6	5.8
		29:01:1978	34.9,25.7	5.7	5.9
4A	1930, 5.6	06:03:1930	34.7,24.5	5.8	5.8
Lybic Sea 1		17:12:1952	34.4,24.5	7.0	7.0
		11:09:1977	34.9,23.0	6.3	6.3
4B	1918, 5.6	06:03:1930	34.5,26.0	5.6	5.6
Lybic Sea 2		12:06:1969	34.4,25.0	6.1	6.2
5a	1922, 5.7	13:08:1922	35.0,26.8	6.8	6.8
Karpathos		09:02:1948	35.5,27.4	7.1	7.1
5b	1481, 7.2	03:10:1481	36.2,28.5	7.2	7.2
Rhodos	1919, 5.6	27:01:1921	36.0,28.0	5.6	5.6
		05:01:1987	36.3,28.5	5.6	5.6
5c	1851, 6.8	28:02:1851	36.4,28.6	7.2	7.2
Marmaris	1926, 5.6	18:03:1926	35.8,29.5	6.9	6.9
		25:04:1957	36.5,28.6	7.2	7.3
5A	1918, 5.5	17:03:1918	35.0,27.5	5.7	5.7
Stravo 1		28:04:1933	35.0,27.2	5.5	5.5
		30:10:1957	35.1,27.2	5.6	5.6
		09:05:1966	34.4,26.4	5.8	5.8
		27:09:1985	34.5,26.6	5.5	5.5
5B	1922, 5.5	11:08:1922	35.4,27.7	6.3	6.3
Stravo 2		30:10:1957	35.2,27.7	5.5	5.5
		30:05:1968	35.4,27.9	5.9	6.0
6a	1843, 6.2	05:09:1843	41.2,20.1	6.2	6.2
Elbasan	1920, 5.5	16:08:1907	41.1,20.1	6.2	6.2
		18:12:1920	41.1,20.1	5.8	6.0
		31:03:1935	41.3,20.3	5.7	5.7
		27:08:1942	41.6,20.4	5.9	6.0
		30:11:1967	41.4,20.4	6.3	6.3

Table 1 (*Contd*)

Source	Completeness	Date	Epicenter	M_s	M
6b	1860, 6.2	10:04:1860	40.2,20.3	6.4	6.5
Tepeleni	1920, 5.5	26:11:1920	40.3,20.0	6.3	6.3
		03:04:1969	40.7,20.0	5.8	5.8
6c	1922, 5.5	07:12:1922	41.8,20.6	6.1	6.1
Maliq		07:01:1953	41.3,20.6	5.6	5.6
		12:03:1960	41.9,20.9	5.7	5.7
6b	1896, 6.0	28:09:1896	41.1,20.7	6.1	6.1
Ochrida		18:02:1911	40.9,20.8	6.7	6.8
		26:05:1960	40.6,20.7	6.5	6.5
6e	1919, 5.5	22:12:1919	40.1,20.7	6.3	6.3
Jannena		01:05:1967	39.5,21.2	6.4	6.4
6f	1915, 5.5	04:06:1915	39.1,21.5	5.8	5.8
Karpenisi		05:02:1966	39.1,21.7	6.2	6.2
7a	1846, 6.1	11:06:1846	37.1,22.0	6.4	6.4
Kalamata	1901, 5.5	24:12:1901	37.2,22.2	5.8	5.9
		13:04:1955	37.2,22.3	5.9	5.9
		05:04:1965	37.7,22.0	6.1	6.3
		13:09:1986	37.1,22.1	6.0	6.0
7b	1842, 6.4	18:04:1842	36.7,22.3	6.4	6.4
Sparti	1901, 5.5	25:10:1901	36.9,22.3	5.5	5.5
		30:07:1944	36.7,22.5	6.0	6.0
7c	1798, 6.4	00:06:1798	36.0,23.0	6.4	6.4
Kythera	1913, 5.5	06:07:1913	35.9,23.2	5.7	5.7
		27:04:1965	35.6,23.5	5.7	5.7
7b	1918, 5.5	29:02:1940	35.7,25.9	6.0	6.2
Sitia		30:07:1956	35.8,26.0	6.0	6.1
		22:09:1975	35.2,26.3	5.5	5.7
		05:09:1988	35.2,26.3	5.5	5.5
7e	1956, 5.5	28:04:1962	36.1,26.8	5.8	5.9
Karpathos Sea					
7f	1896, 6.7	27:10:1896	36.6,27.9	6.7	6.7
Symi	1918, 5.6	01:09:1942	36.4,27.4	5.8	5.9
8a	1804, 6.0	08:06:1804	38.2,21.7	6.6	6.7
Patra	1914, 5.7	24:12:1917	38.4,21.8	6.0	6.0
		30:06:1975	38.5,21.7	5.7	5.9
8b	1748, 6.3	25:05:1748	38.2,22.2	6.8	6.8
W. Corinthiakos	1909, 5.6	23:08:1817	38.2,22.1	6.5	6.5
		01:08:1870	38.5,22.5	6.8	7.0
		30:05:1909	38.4,22.2	6.2	6.2
		06:07:1965	38.4,22.4	6.3	6.5
8c	1858, 6.7	21:02:1858	37.9,22.9	6.7	6.7
E. Corinthiakos	1916, 5.5	22:04:1928	37.9,23.0	6.3	6.4
		05:09:1953	37.9,23.1	5.8	5.9
		24:02:1981	38.2,23.0	6.7	6.8

Table 1 (*Contd*)

Source	Completeness	Date	Epicenter	M_s	M
9a	1873, 5.5	25:07:1873	37.7,23.2	6.0	6.0
Methana		08:08:1922	37.5,23.2	5.6	5.6
		04:07:1968	37.8,23.2	5.5	5.5
9b	1733, 6.4	20:07:1938	36.8,24.5	6.5	6.7
Milos	1918, 5.5				
9c	1866, 6.1	31:01:1866	36.4,25.4	6.2	6.2
Santorini	1919, 5.5	25:10:1919	36.7,25.6	6.1	6.1
		09:07:1956	36.7,25.8	7.5	7.6
9d	1920, 5.6	23:04:1933	36.8,27.3	6.6	6.6
Kos		23:02:1961	36.7,27.1	5.6	5.6
		05:12:1968	36.6,26.9	6.0	6.1
9e	1869, 6.2	01:12:1869	37.0,28.1	6.8	6.8
Alicarnasos	1920, 5.5	13:12:1941	37.2,28.3	6.2	6.4
		25:04:1959	37.0,28.5	6.2	6.2
		28:04:1989	37.0,27.9	5.5	5.5
9f	1920, 5.5	01:03:1926	37.0,29.4	6.2	6.2
Denisli		30:01:1964	37.4,29.9	5.5	5.5
10	1905, 5.5	20:01:1905	39.6,23.0	6.0	6.2
Thessalia		31:03:1930	39.5,23.0	6.1	6.3
		01:03:1941	39.6,22.5	6.3	6.3
		30:04:1954	39.3,22.2	7.0	7.2
		09:07:1980	39.2,23.1	6.5	6.6
11a	1758, 6.0	00:05:1758	38.9,22.7	6.8	6.8
N. Evoikos	1902, 5.5	18:03:1874	38.6,23.5	6.0	6.0
		27:04:1894	38.7,23.0	7.0	7.1
		27:09:1916	38.9,23.0	5.9	6.0
11b	1853, 6.0	18:08:1853	38.3,23.3	6.8	6.8
S. Evoikos	1912, 5.5	23:05:1893	38.3,23.4	6.2	6.2
		17:10:1914	38.3,23.4	6.0	6.1
		20:07:1938	38.3,23.8	6.0	6.0
12a	1865, 6.0	31:01:1873	37.8,27.1	6.6	6.8
Samos	1904, 5.8	12:03:1893	37.9,26.9	6.6	6.6
		11:08:1904	37.7,26.9	6.9	6.9
		16:07:1955	37.6,27.2	6.9	6.9
12b	1899, 6.2	20:09:1899	37.9,28.8	7.0	7.0
Aidin	1963, 5.5	12:05:1971	37.6,29.7	6.2	6.3
		11:10:1986	38.0,29.0	6.0	6.0
13a	1890, 6.0	26:05:1890	38.5,25.5	6.2	6.2
Psara	1921, 5.5	14:03:1933	38.4,25.3	5.5	5.5
		29:03:1986	38.4,25.2	5.8	6.0
13b	1856, 6.4	13:11:1856	38.4,26.1	6.6	6.6
Chios	1931, 5.5	15:10:1883	38.3,26.4	6.5	6.7
		23:07:1949	38.6,26.3	6.7	6.7
		06:04:1969	38.5,26.4	5.9	5.9

Table 1 (*Contd*)

Source	Completeness	Date	Epicenter	M_s	M
13c	1880, 6.5	29:07:1880	38.6,27.1	6.7	6.7
Ismir	1904, 5.5	10:10:1904	38.4,27.2	5.8	5.9
		31:03:1928	38.2,27.4	6.5	6.6
		01:02:1974	38.5,27.2	5.5	5.7
13d	1918, 5.5	16:01:1918	38.3,29.5	5.7	5.7
Alasehir		29:07:1933	38.2,29.8	5.9	5.9
		28:03:1969	38.5,28.5	6.6	6.6
14a	1916, 5.5	05:12:1923	39.8,23.5	6.4	6.5
Skopelos		04:06:1947	40.0,24.0	6.1	6.1
		09:03:1965	39.3,23.8	6.1	6.2
		18:01:1982	39.8,24.4	6.9	6.9
14b	1947, 5.5	12:04:1947	39.7,25.2	5.7	5.7
Ag. Eustratios		19:02:1968	39.4,24.9	7.1	7.2
14c	1845, 6.5	11:10:1845	39.0,26.2	6.8	6.8
Lesbos	1919, 5.6	07:03:1867	39.2,26.4	6.8	7.0
		25:10:1889	39.2,25.8	6.7	6.7
		18:11:1919	39.3,26.7	7.0	7.0
		06:10:1944	39.4,26.7	6.9	7.1
		19:12:1981	39.2,25.2	7.2	7.3
14d	1942, 5.5	15:11:1942	39.4,28.1	6.2	6.4
Demirci		23:03:1969	39.1,28.5	6.1	6.3
14e	1928, 5.5	02:05:1928	39.6,29.1	6.2	6.2
Gediz		25:06:1944	39.0,29.3	6.1	6.3
		28:03:1970	39.2,29.5	7.1	7.1
15a	1766, 7.4	05:08:1766	41.0,27.5	7.7	7.7
Hellispondos	1912, 6.0	09:08:1912	40.6,27.2	7.6	7.6
		04:01:1935	40.4,27.5	6.4	6.6
		18:03:1953	40.0,27.4	7.4	7.4
		05:07:1983	40.3,27.2	6.1	6.1
15b	1855, 6.9	28:02:1855	40.2,29.1	7.2	7.3
Prusa	1905, 5.7	15:09:1939	39.8,29.6	5.7	5.7
		19:03:1952	39.8,28.7	5.8	6.0
		06:10:1964	40.3,28.2	6.9	6.9
16a	1905, 5.5	08:11:1905	40.3,24.4	7.5	7.5
Athos		03:08:1954	40.1,24.5	5.9	6.0
		20:12:1965	40.2,24.8	5.6	5.8
		06:08:1983	40.0,24.7	6.8	6.8
16b	1893, 6.5	09:02:1893	40.4,25.5	6.5	6.5
Samothraki	1917, 5.5	20:08:1917	40.3,25.4	5.7	5.7
		02:06:1955	40.4,25.8	5.5	5.5
		23:08:1965	40.5,26.2	5.6	5.6
		27:03:1975	40.4,26.1	6.6	6.6
17a	1902, 5.7	05:07:1902	40.8,23.1	6.5	6.5
Volvi		26:09:1932	40.5,23.9	7.0	7.1
		20:06:1978	40.8,23.2	6.5	6.5

Table 1 (*Contd*)

Source	Completeness	Date	Epicenter	M_s	M
17b	1905, 5.5	18:11:1905	41.0,23.0	5.6	5.6
Doirani		08:03:1931	41.3,22.5	6.7	6.7
		21:12:1990	41.0,22.4	5.9	5.9
17c	1866, 6.5	06:12:1866	42.0,23.0	7.0	7.0
Kresna	1903, 5.5	04:04:1904	41.8,23.1	7.7	7.8
17A	1921, 5.5	10:08:1921	42.3,21.4	5.8	5.8
Skopje		26:07:1963	42.0,21.4	6.1	6.1
18	1784, 6.3	06:11:1784	41.0,25.3	6.3	6.3
Drama	1911, 5.5	05:05:1829	41.1,24.3	7.3	7.4
		09:11:1985	41.2,23.9	5.5	5.5
19a	1641, 6.9	00:05:1641	42.2,23.7	6.9	6.9
Velingrad	1904, 5.5	04:04:1904	42.1,23.4	5.5	5.5
		03:11:1977	42.1,24.0	5.5	5.5
19b	1750, 6.8	00:10:1750	42.1,24.8	6.8	6.8
Philippoupoli	1924, 5.5	18:04:1928	42.2,25.0	7.0	7.2

sample (occurred in 1948) has a magnitude $M_{\min} = 5.6$. The first repeat time ($T = 43.24$ years), which holds for this minimum, is the interevent time between the mainshock which occurred on 1.6.1905 ($M_p = 6.6$, $t_p = 1905$) and the mainshock which occurred on 27.8.1948 ($M_f = 5.6$, $t_f = 1948$) and is written in the first line of Table 2 in which the corresponding values of $M_{\min}$, M_p, M_f, t_p and t_f are also given. The second repeat time ($T = 17.98$ years), which also holds for $M_{\min} = 5.6$, is the interevent time between the mainshock which occurred on 27.8.1948 ($M_p = 5.6$, $t_p = 1948$) and the mainshock which occurred on 20.8.1966 ($M_f = 5.7$, $t_f = 1966$) and is written on the second line of Table 2, where the corresponding values of the magnitudes and the years of occurrence are also given. Keeping the same $M_{\min}$ ($= 5.6$), the values of the third line of Table 1 have been determined in the same way.

We now consider the earthquakes with $M > 5.6$, that is, we ignore the earthquakes with $M = 5.6$. Table 1 shows that the smallest earthquake now is $M = 5.7$. There are two repeat times which correspond to this new minimum magnitude. The first one is the interevent time ($T = 61.22$ years) between the mainshock which occurred on 1.6.1905 ($M_p = 6.6$, $t_p = 1905$) and the mainshock which occurred on 20.8.1966 ($M_f = 5.7$, $t_f = 1966$) and these values are written on the fourth line of Table 2. the second one is the interevent time ($T = 12.65$ years) between the main shock which occurred on 20.8.1966 ($M_p = 5.7$, $t_p = 1966$) and the mainshock which occurred on 15.4.1979 ($M_f = 7.1$, $t_f = 1979$).

Table 2

Data used to determine the parameters of the empirical relations

Source	$M_{\min}$	M_p	M_f	T	t_p	t_f
1a	5.6	6.6	5.6	43.24	1905	1948
		5.6	5.7	17.98	1948	1966
		5.7	7.1	12.65	1966	1979
	5.7	6.6	5.7	61.22	1905	1966
		5.7	7.1	12.65	1961	1979
	6.5	6.5	6.6	49.91	1855	1905
		6.6	7.1	73.87	1905	1979
	6.6	6.6	7.1	73.87	1905	1979
1b	5.6	6.2	6.5	32.71	1926	1959
		6.5	5.6	28.35	1959	1988
	6.2	6.5	6.2	56.22	1870	1926
		6.2	6.5	32.71	1926	1959
	6.5	6.5	6.5	88.93	1870	1959
1c	5.7	6.3	6.0	31.33	1930	1962
		6.0	5.7	20.66	1962	1982
	6.0	6.3	6.0	31.33	1930	1962
	6.3	6.5	6.3	37.35	1893	1930
1d	5.5	6.1	6.0	46.30	1920	1967
		6.0	6.0	14.09	1967	1981
		6.0	5.5	9.27	1981	1990
	6.0	6.1	6.0	46.30	1920	1967
		6.0	6.0	14.09	1967	1981
1e	6.0	6.0	6.2	30.21	1891	1921
		6.2	6.2	45.13	1921	1966
	6.2	6.2	6.2	45.13	1921	1966
2a	5.9	6.4	5.9	23.30	1914	1938
		5.9	6.8	10.11	1938	1948
		6.8	5.9	25.53	1948	1973
	6.4	6.7	6.6	44.94	1825	1869
		6.6	6.4	44.92	1869	1914
		6.4	6.8	33.40	1914	1948
	6.6	6.7	6.6	44.94	1925	1869
		6.6	6.8	78.32	1869	1948
	6.7	6.7	6.8	123.26	1825	1948
2b	6.3	7.2	7.2	44.97	1867	1912
		7.2	7.4	41.55	1912	1953
		7.4	6.3	19.10	1953	1972
		6.3	7.0	10.33	1972	1983
	7.0	7.2	7.2	44.97	1867	1912
		7.2	7.4	41.55	1912	1953
		7.4	7.0	29.43	1953	1983
	7.2	7.2	7.2	99.53	1767	1867
		7.2	7.2	44.97	1867	1912
		7.2	7.4	41.55	1912	1953

Table 2 (*Contd*)

Source	$M_{\min}$	M_p	M_f	T	t_p	t_f
2c	6.0	6.7	6.1	32.99	1840	1873
		6.1	6.4	19.48	1873	1893
		6.4	6.3	46.42	1893	1939
		6.3	6.9	20.15	1939	1959
		6.9	6.0	28.92	1959	1988
	6.1	6.7	6.1	32.99	1840	1873
		6.1	6.4	19.48	1873	1893
		6.4	6.3	46.42	1893	1939
		6.3	6.9	20.15	1939	1959
	6.3	6.7	6.4	52.47	1840	1893
		6.4	6.3	46.42	1893	1939
		6.3	6.9	20.15	1939	1959
	6.4	6.7	6.4	52.47	1840	1893
		6.4	6.9	66.58	1893	1959
	6.7	6.7	6.9	119.04	1840	1959
2A	6.0	6.0	6.6	15.54	1943	1958
		6.6	6.6	17.71	1958	1976
	6.6	6.6	6.6	17.71	1958	1976
3a	5.9	7.0	5.9	41.87	1947	1989
	7.0	7.5	7.0	61.11	1886	1947
3b	5.6	5.6	5.6	18.92	1932	1951
		5.6	5.7	6.34	1951	1958
3A	6.0	6.4	6.0	28.27	1919	1947
		6.0	6.0	16.54	1947	1963
3B	6.3	6.4	6.3	35.35	1926	1962
4a	6.2	6.4	6.3	11.70	1947	1959
		6.3	6.6	12.97	1959	1972
		6.6	6.2	12.13	1972	1984
	6.3	6.4	6.3	11.70	1947	1959
		6.3	6.6	12.97	1959	1972
	6.4	6.4	6.6	24.68	1947	1972
4b	5.6	5.6	5.8	10.88	1927	1938
		5.8	5.9	39.97	1938	1978
	5.8	5.8	5.9	39.97	1938	1978
4A	5.8	5.8	7.0	22.78	1930	1952
		7.0	6.3	24.73	1952	1977
	6.3	7.0	6.3	24.73	1952	1977
4B	5.6	5.6	6.2	39.27	1930	1969
5a	6.8	6.8	7.1	25.49	1922	1948
5b	5.6	5.6	5.6	65.94	1921	1987
5c	6.9	7.2	6.9	75.06	1851	1926
		6.9	7.3	31.10	1926	1957
	7.2	7.2	7.3	106.16	1851	1957

Table 2 (*Contd*)

Source	$M_{\min}$	M_p	M_f	T	t_p	t_f
5A	5.5	5.7	5.5	15.11	1918	1933
		5.5	5.6	24.50	1933	1957
		5.6	5.8	8.53	1957	1966
		5.8	5.5	19.38	1966	1985
	5.6	5.7	5.6	39.62	1918	1957
		5.6	5.8	8.53	1957	1966
	5.7	5.7	5.8	48.15	1918	1966
5B	5.5	6.3	5.5	35.22	1922	1957
		5.5	6.0	10.58	1957	1968
	6.0	6.3	6.0	45.80	1922	1968
6a	5.7	6.0	5.7	14.29	1920	1935
		5.7	6.0	7.41	1935	1942
		6.0	6.3	25.26	1942	1967
	6.0	6.0	6.0	21.69	1920	1942
		6.0	6.3	25.26	1942	1967
	6.2	6.2	6.2	63.95	1843	1907
		6.2	6.3	60.29	1907	1967
6b	5.8	6.3	5.8	48.36	1920	1969
	6.3	6.5	6.3	60.63	1860	1920
6c	5.6	6.1	5.6	30.08	1922	1953
		5.6	5.7	7.18	1953	1960
	5.7	6.1	5.7	37.26	1922	1960
6d	6.1	6.1	6.8	14.39	1869	1911
		6.8	6.5	49.27	1911	1960
	6.5	6.8	6.5	49.27	1911	1960
6e	6.3	6.3	6.4	47.36	1919	1967
6f	5.8	5.8	6.2	50.67	1915	1966
7a	5.9	5.9	5.9	53.30	1901	1955
		5.9	6.3	9.98	1955	1965
		6.3	6.0	21.44	1965	1986
	6.0	6.3	6.0	21.44	1965	1986
	6.3	6.4	6.3	118.82	1846	1965
7b	5.5	5.5	6.0	42.76	1901	1944
7c	5.7	5.7	5.7	51.81	1913	1965
7d	5.5	6.2	6.1	16.42	1940	1956
		6.1	5.7	19.15	1956	1975
		5.7	5.5	12.95	1975	1988
	5.7	6.2	6.1	16.42	1940	1956
		6.1	5.7	19.15	1956	1975
	6.1	6.2	6.1	16.42	1940	1956
7e	—	—	—	—	—	—
7f	—	—	—	—	—	—
8a	5.9	6.0	5.9	57.52	1917	1975
	6.0	6.7	6.0	113.54	1804	1917

Table 2 (*Contd*)

Source	$M_{\min}$	M_p	M_f	T	t_p	t_f
8b	6.2	6.2	6.5	56.10	1909	1965
	6.5	6.8	6.5	69.24	1748	1817
		6.5	7.0	52.94	1817	1870
		7.0	6.5	94.93	1870	1965
	6.8	6.8	7.0	122.19	1748	1870
8c	5.9	6.4	5.9	25.37	1928	1953
		5.9	6.8	27.47	1953	1981
	6.4	6.4	6.8	53.84	1928	1981
	6.7	6.7	6.8	123.01	1858	1981
9a	5.5	6.0	5.6	49.04	1873	1922
		5.6	5.5	45.91	1922	1968
	5.6	6.0	5.6	49.04	1873	1922
9b	—	—	—	—	—	—
9c	6.1	6.2	6.1	53.73	1866	1919
		6.1	7.6	36.70	1919	1956
	6.2	6.2	7.6	90.44	1866	1956
9d	5.6	6.6	5.6	27.84	1933	1961
		5.6	6.1	7.78	1961	1968
	6.1	6.6	6.1	35.62	1933	1968
9e	5.5	6.4	6.2	17.37	1941	1959
		6.2	5.5	30.01	1959	1989
	6.2	6.8	6.4	72.03	1869	1941
		6.4	6.2	17.37	1941	1959
	6.4	6.8	6.4	72.03	1869	1941
9f	5.5	6.2	5.5	37.91	1926	1964
10	6.2	6.2	6.3	25.20	1905	1930
		6.3	6.3	10.92	1930	1941
		6.3	7.2	13.16	1941	1954
		7.2	6.6	26.19	1954	1980
	6.3	6.3	6.3	10.92	1930	1941
		6.3	7.2	13.16	1941	1954
		7.2	6.6	26.19	1954	1980
	6.6	7.2	6.6	26.19	1954	1980
11a	6.0	6.8	6.0	115.80	1758	1874
		6.0	7.1	20.11	1874	1894
		7.1	6.0	22.42	1894	1916
	6.8	6.8	7.1	135.91	1758	1894
11b	6.0	6.8	6.2	39.77	1853	1893
		6.2	6.1	21.40	1893	1914
		6.1	6.0	23.76	1914	1938
	6.1	6.8	6.2	39.77	1853	1893
		6.2	6.1	21.40	1893	1914
	6.2	6.8	6.2	39.77	1853	1893

Table 2 (*Contd*)

Source	$M_{\min}$	M_p	M_f	T	t_p	t_f
12a	6.6	6.8	6.6	20.11	1873	1893
		6.6	6.9	11.41	1893	1904
		6.9	6.9	50.93	1904	1955
	6.8	6.8	6.9	31.53	1873	1904
		6.9	6.9	50.93	1904	1955
	6.9	6.9	6.9	50.93	1904	1955
12b	6.0	6.3	6.0	15.41	1971	1986
	6.3	7.0	6.3	71.65	1899	1971
13a	5.5	5.5	6.0	53.04	1933	1986
	6.0	6.2	6.0	95.84	1890	1986
13b	5.9	6.7	5.9	19.70	1949	1969
	6.6	6.6	6.7	26.92	1856	1883
		6.7	6.7	65.77	1883	1949
	6.7	6.7	6.7	65.77	1883	1949
13c	5.7	5.9	6.6	23.47	1904	1928
		6.6	5.7	45.83	1928	1974
	5.9	5.9	6.6	23.47	1904	1928
	6.6	6.7	6.6	47.67	1880	1928
13d	5.7	5.7	5.9	15.51	1918	1933
		5.9	6.6	35.69	1933	1969
	5.9	5.9	6.6	35.69	1933	1969
14a	6.1	6.5	6.1	23.50	1923	1947
		6.1	6.2	17.76	1947	1965
		6.2	6.9	16.86	1965	1982
	6.2	6.5	6.2	41.26	1923	1965
		6.2	6.9	16.86	1965	1982
	6.5	6.5	6.9	58.12	1923	1982
14b	5.7	5.7	7.2	20.85	1947	1968
14c	6.7	6.8	7.0	21.41	1845	1867
		7.0	6.7	22.63	1867	1889
		6.7	7.0	30.06	1889	1919
		7.0	7.1	24.88	1919	1944
		7.1	7.3	37.20	1944	1981
	6.8	6.8	7.0	21.41	1845	1867
		7.0	7.0	52.70	1867	1919
		7.0	7.1	24.88	1919	1944
		7.1	7.3	37.20	1944	1981
	7.0	7.0	7.0	52.70	1867	1919
		7.0	7.1	24.88	1919	1944
		7.1	7.3	37.20	1944	1981
	7.1	7.1	7.3	37.20	1944	1981
14d	6.3	6.4	6.3	26.36	1942	1969
14e	6.2	6.2	6.3	16.14	1928	1944
		6.3	7.1	25.76	1944	1970
	6.3	6.3	7.1	25.76	1944	1970

Table 2 (*Contd*)

Source	$M_{\min}$	M_p	M_f	T	t_p	t_f
15a	6.1	7.6	6.6	22.40	1912	1935
		6.6	7.4	18.21	1935	1953
		7.4	6.1	30.30	1953	1983
	6.6	7.6	6.6	22.40	1912	1935
		6.6	7.4	18.21	1935	1953
	7.4	7.7	7.6	146.01	1766	1912
		7.6	7.4	40.61	1912	1953
	7.6	7.7	7.6	146.01	1766	1912
15b	5.7	5.7	6.0	12.51	1939	1952
		6.0	6.9	12.55	1952	1964
	6.0	6.0	6.9	12.55	1952	1964
	6.9	7.3	6.9	109.61	1855	1964
16a	5.8	7.5	6.0	48.74	1905	1954
		6.0	5.8	11.38	1954	1965
		5.8	6.8	17.63	1965	1983
	6.0	7.5	6.0	48.74	1905	1954
		6.0	6.8	29.01	1954	1983
	6.8	7.5	6.8	77.74	1905	1983
16b	5.5	5.7	5.5	37.78	1917	1955
		5.5	5.6	10.22	1955	1965
		5.6	6.6	9.59	1965	1975
	5.6	5.7	5.6	48.01	1917	1965
		5.6	6.6	9.59	1965	1975
	5.7	5.7	6.6	57.60	1917	1975
	6.5	6.5	6.6	82.13	1893	1975
17a	6.5	6.5	7.1	30.22	1902	1932
		7.1	6.5	45.73	1932	1978
17b	5.6	5.6	6.7	25.30	1905	1931
	5.6	6.7	5.9	59.79	1931	1990
	5.9	6.7	5.9	59.79	1931	1990
17c	7.0	7.0	7.8	37.33	1866	1904
17A	5.8	5.8	6.1	41.96	1921	1963
18	6.3	6.3	7.4	44.50	1784	1829
19a	5.5	5.5	5.5	73.58	1904	1977
19b	6.8	6.8	7.2	177.47	1750	1928

The next step is to consider the earthquakes with $M > 5.7$, that is, to ignore the earthquakes with $M \leq 5.7$. Table 1 shows that the smallest earthquake now is $M_{\min} = 6.5$, that is, the remaining earthquakes now belong to the second complete sample of data (1855–1990, $M \geq 6.5$). Working in the same way as above we determined three additional sets of $M_{\min}$, M_p, M_f, T, t_p, t_f which are written on the last three lines for source 1a of Table 1.

Relation Between the Repeat Times and the Magnitudes of the Preceding and Minimum Mainshocks

The values $b = 0.41$, $c = 0.28$ of the relation (1) between the repeat time, T, and the magnitudes $M_{\min}$, M_p were determined by the use of data for only seven seismogenic sources (PAPAZACHOS, 1988b). Since we now have considerably more available data we can calculate these parameters more accurately. These data concern the 49 seismogenic sources for which at least two time periods (three mainshocks) are available for each source. Thus a total number of about 240 repeat times were used and the following method was applied for this purpose.

By the use of the b and c values mentioned above as initial ones, an initial mean value for parameter a_i of each source was calculated by the relation (1). Each source's data was corrected by subtracting a_i from $\log T$. Now, relation (1) can be written as

$$y = \log T - a_i = bM_{\min} + cM_p. \tag{2}$$

Applying least squares differential correction on the whole data set (for all 49 sources), values of b and c as well as the standard deviation, σ_y, and the multilinear correlation coefficient, R, for equation (2) were calculated. Using the new values of b and c, the procedure was repeated until convergence was achieved, that is, stable values for b, c and a. The final values for the first two of these parameters are

$$b = 0.36, \quad c = 0.35 \tag{3}$$

and the corresponding values for the standard deviation and the multiple correlation coefficient are $\sigma_y = 0.16$ and $R = 0.89$.

Figure 2 displays a plot of $\log T^* = \log T - bM_{\min} - a$, as a function of M_p, where T, $M_{\min}$, M_p are observed values, $b = 0.36$ and "a" the value of this parameter determined for each source. The line drawn through the data is a least squares fit.

The same procedure as described above has also been applied in searching for a relation of the form $\log T = b'M_{\min} + c'M_f + a'$ between the repeat time, T, and the magnitude, M_f, of the following mainchock and the minimum magnitude, $M_{\min}$, considered. The values $b' = 0.64$, and $c' = -0.14$ were found, with a multilinear correlation coefficient equal to 0.80.

It is clear that the dependence of the repeat time on the magnitude of the preceding mainshock is strong and positive ($c = 0.35$), while the dependence of the following mainshock on the repeat time is weak and negative ($c = -0.14$). This shows that the time-predictable model holds for the seismogenic sources of shallow earthquakes in the Aegean and surrounding area and that the slip-predictable model does not hold for these sources.

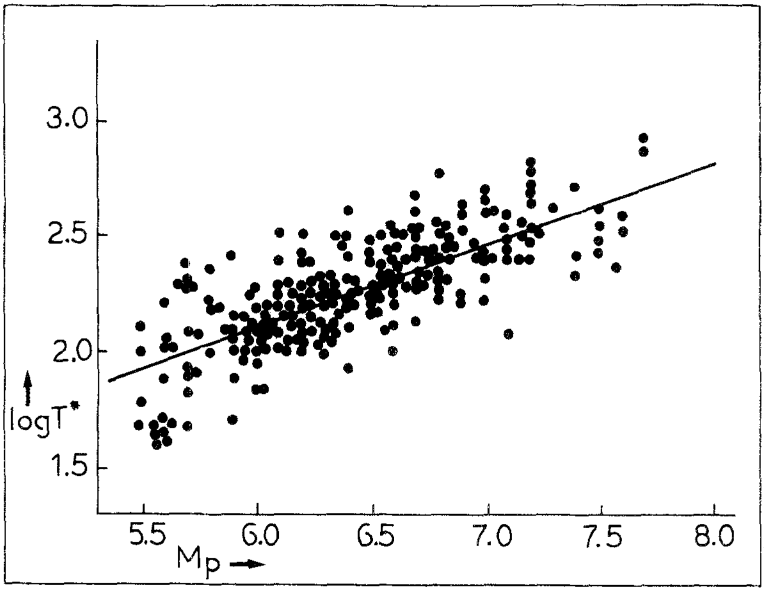

Figure 2
Dependence of the repeat time on the magnitude of the preceding mainshock.

Relation Between the Magnitude of the Following Mainshock and the Magnitudes of the Preceding and the Minimum Mainshocks

A negative dependence of the magnitude, M_f, of the following mainshock on the interevent time has been observed for seven seismogenic sources in Greece (PAPAZACHOS, 1989). The equivalent dependence is also observed for 49 seismogenic sources investigated in the present paper. Since both samples of data show a positive correlation between the interevent time and the magnitude, M_p, of the preceding earthquake, we may expect a negative dependence of M_f on M_p. Because M_f depends also on $M_{\min}$ we may expect a relation of the form:

$$M_f = BM_{\min} + CM_p + m \tag{4}$$

where B, C are constants which can be assumed to the same for all seismogenic sources and m constant which varies from source to source.

By applying the same method which has been applied to determine b and c of relation (1), the values

$$B = 0.85, \quad C = -0.49 \tag{5}$$

were found. A standard deviation $\sigma_y = 0.25$ and a multilinear correlation coefficient $R = 0.72$ were determined for (4).

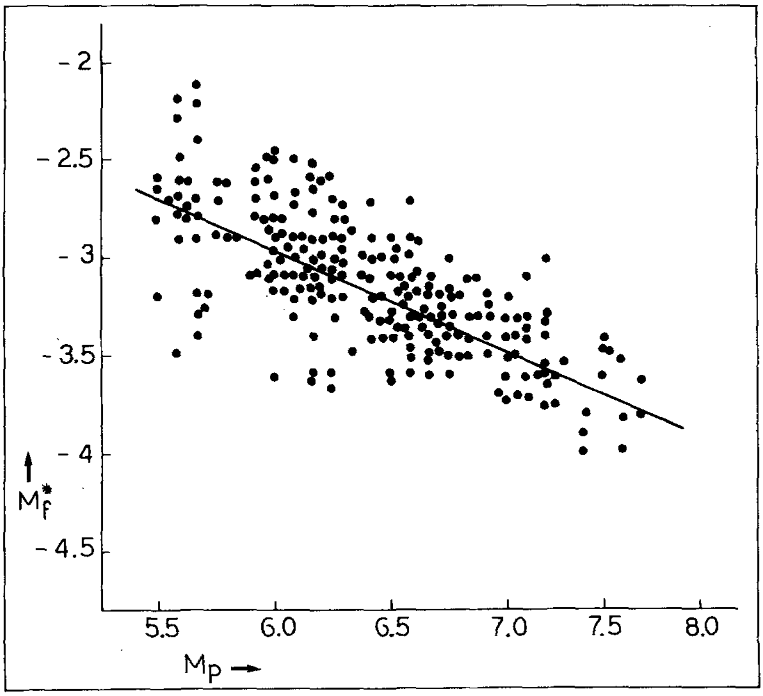

Figure 3

Dependence of the magnitude of the following mainshock on the magnitude of the preceding mainshock.

The $M_f^* = M_f - BM_{\min} - m$, where M_f and $M_{\min}$ are the observed values, $B = 0.85$, and m the value of this parameter calculated for each source, is plotted versus the observed M_p in Figure 3 for all 240 observations (with the exception of two much diverging observations). The straight line is a least squares fit. Although the scatter in Figure 3 is rather large, these data do show that a small mainshock in a certain seismogenic source is more likely to be followed by a large mainshock and *vice versa*.

A Time- and Magnitude-predictable Model for the Generation of Strong Shallow Earthquakes

Figure 4 presents schematically a simple model for the generation of the shallow mainshocks larger than a certain magnitude (e.g., $M_s \geq 5.7$) in the seismogenic sources of the Aegean and the surrounding area. It shows the time variation of stress in a seismogenic source and assumes that stress is accumulated at a constant rate (inclined lines are parallel) and is released during the generation of the mainshock.

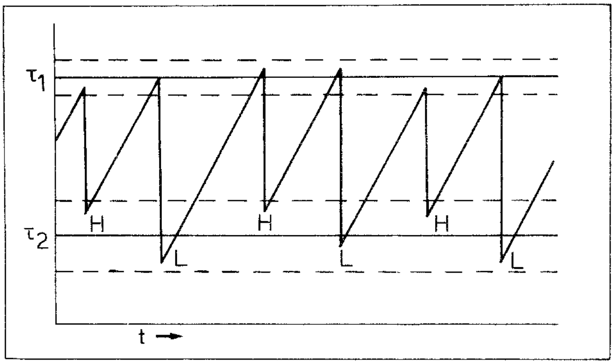

Figure 4
Schematic representation of the time variation of stress in a seismogenic source for the model proposed in the present paper. The maximum stress, τ_1, values fluctuate within a relatively narrow stress interval and the minimum stress, τ_2, values fluctuate within a considerably broader interval. The minimum stress values, however, follow a statistical law according to which low values (L) are typically followed by high values (H) and *vice versa*.

The maximum values of the stress in several seismic cycles do not exactly reach the same stress level, τ_1, but fluctuate in a rather narrow stress interval (upper dashed lines) around this level (relatively small scatter of the observed repeat times with respect to those given by relation (1)) and therefore a reliable statistical prediction of the recurrence time can be made.

The minimum stress values fluctuate in a much broader stress interval (lower dashed lines) around a lower stress value, τ_2, and for this reason no reliable prediction of the magnitude of the next earthquake can be made on the basis of the limits of this interval. However, the minimum values of the stress in the different seismic cycles seem to follow a statistical law (expressed by relation (4)), that is, each of these values becomes lower or higher than τ_2 if the previous one is higher or lower than τ_2, respectively.

It is, therefore, possible to predict, in principle, both the time and the magnitude of the next main shock in each seismogenic source by this model, as it is expressed by relations (1) and (4). However, to do this, in practice, one has to define the statistical law which is followed by the maxima of the earthquake size; and such work is in progress.

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