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Earthquake Triggering in the North and East Aegean Plate Boundaries due to the Anatolia Westward Motion

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Abstract. Historical and instrumental data of the last five centuries show that major earthquakes in the Marmara Sea area are followed by high strong-earthquake seismicity in the Aegean area. During the first phase of this excitation period, which lasts about 3 years, strong shallow earthquakes concentrate almost exclusively along the Northern Boundary of the Aegean plate. Within 1-5 years after the first strong earthquake along this boundary, strong-earthquake seismicity also increases in the Eastern Aegean Boundary. On the basis of current ideas on active tectonics and the previous observations, we expect the generation of several mainshocks with a mean magnitude of M=6.5 along the Northern Aegean Boundary during the next 3 years, following the recent large Izmit (NW Turkey) earthquake (1999.8.17, M=7.4).

Introduction

Significant scientific information on the active tectonics of the broader Aegean area has been obtained during the last three decades by the use of seismological and geodetic data [*Papazachos and Comninakis,* 1971; *McKenzie,* 1972; *Taymaz et al.,* 1991; *Straub et al.,* 1997; *Papazachos,* 1999]. These studies suggest that active tectonics in this area are mainly controlled by the westward motion of the Anatolia plate and the fast southwestward motion of the Aegean plate. These motions create a deformation belt along the Northern Boundary of the Aegean plate (Marmara Sea-Northern Aegean trough-central Greece-Ionian islands), called NAB in the present paper, where dextral strike-slip ruptures dominate. The same geotectonic processes led to the formation of an extensional field in the Aegean, which is very intense along the Eastern Aegean plate Boundary, called EAB hereinafter.

Migration of seismic activity in these two belts has already been observed by several investigators, especially regarding the westward migration of the epicenters along the Northern Anatolia Fault (NAF) [*Ketin,* 1969; *Toksoz et al.,* 1979]. *Galanopoulos*[1971] also noticed that strong earthquakes in western Aegean are followed by similar earthquakes in its eastern part and vice versa. Other results [*Papazachos and Papadimitriou,* 1984] describe the eastward migration of strong earthquakes (M$\geq$6.0) along the broader area of northern Aegean during the period 1954-1970.

In the present paper we examine the migration of seismic activity along the two previously mentioned boundaries of the Aegean Plate using data for strong earthquakes of the last five centuries. Hence, on the basis of recent knowledge concerning active tectonics, as well as reliable observations of the space-time distribution of large earthquakes, realistic estimation of the near-future evolution of the seismic activity can be made. This information is very significant, due to the recent destructive Izmit earthquake (1999.8.17, M=7.4) in the western part of the Northern Anatolia and its possible effect on the Aegean area seismicity and seismic hazard.

Time-Space Distribution of Postshocks

The data set used in the present study consists of: a) Major mainshocks (M$\geq$7.3) which occurred during 1500-1998 in the western part of the Northern Anatolia fault zone (40.0°N-41.5°N, 26.5°E-30.0°E), b) Major mainshocks (M$\geq$7.0) which occurred during 1700-1998 in the same area, c) Strong mainshocks (M$\geq$6.4) in the broader Aegean area (34°N-42°N, 19°E-30°E) which followed each one of these Anatolian earthquakes within 10 years and, d) Strong mainshocks (M$\geq$6.0) in the same area of the instrumental period (1911-1998). Only mainshocks were used in order to have the necessary accuracy for events before the instrumental period. Typical epicenter errors are less than 40 Km, while the magnitude error is less than 0.4 [*Papazachos and Papazachou,* 1997]. All magnitudes considered in this study are either originally estimated or converted (from other scales) moment magnitudes.

Ten major mainshocks (M$\geq$7.0) which occurred in the examined part of the Northern Anatolia fault zone have been identified. We have also included two other major mainshocks (M=7.1, 1957.5.26; M=7.2, 1967.7.27) which had a similar effect on the Aegean seismicity, although their epicenters are located further east, but close, to the epicenter of the destructive Izmit earthquake of 17 August 1999. Information on these 12 major mainshocks, as well as on the strong shocks which followed in the Aegean area is given in Table (1). This data set can be used to investigate the occurrence time and spatial distribution behavior of the strong (M$\geq$6.4) Aegean shocks (postshocks) which follow the major (M$\geq$7.0) Marmara earthquakes. The distribution of the time lag between each of the postshocks and the preceding major Marmara earthquakes shows that the annual rate of postshocks between 0 to 5 years is approximately 250% larger than the corresponding rate between 5 and 10 years after each Marmara "mainshock". Thus, from the 46 postshocks listed in Table (1), 33 occurred within 5 years after the generation of the major Marmara earthquakes and only 13 postshocks between 5 to 10 years, which is the first evidence that major Marmara Sea earthquakes trigger strong earthquakes in the Aegean area.

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Table 1. Date, epicenter, magnitude and maximum MM intensity of the 12 large ($M \geq 7.0$) Marmara earthquakes (bold lines) and the strong ($M \geq 6.4$) Aegean earthquakes which follow within a period of 10 years [*Papazachos and Papazachou,* 1997].

N	Event	M/I_{MM}	N	Event	M/I_{MM}	N	Event	M/I_{MM}
1	**1509.09.10/41.10,28.80**	**7.4/X**	**6**	**1766.08.05/40.74,27.11**	**7.6/X**	**10**	**1953.03.18/40.02,27.53**	**7.4/IX**
N	1511.05.26/40.20,24.70	6.6/VII	N	1767.07.11/38.30,20.40	7.2/X	N	1953.08.12/38.10,20.60	7.2/X
	1514.04.16/37.70,21.00	6.5/VIII		1769.10.12/38.80,20.60	6.7/IX		1954.04.30/39.28,22.29	7.0/IX
2	**1659.02.17/41.00,27.80**	**7.4/VIII**	E	1772.11.24/38.80,26.70	6.4/VIII	E	1955.07.16/37.55,27.05	6.9/VIII
N	1660.03.—/38.30,22.40	6.4/VIII		1773.03.15/39.30,22.70	6.4/VIII		1956.07.09/36.64,25.96	7.5/IX
	1664.—.—/37.90,21.00	6.6/VIII	**7**	**1794.08.05/40.10,29.70**	**7.0/VII**		1957.03.08/39.38,22.63	6.8/IX
3	**1719.05.25/40.66,29.58**	**7.0/X**	N	1797.03.—/40.30,24.80	6.6/VI		1957.04.25/36.50,28.60	7.2/VIII
N	1719.07.23/40.40,26.00	6.7/VII		1804.06.08/38.20,21.70	6.4/IX	**11**	**1957.05.26/40.60,31.20**	**7.1/IX**
	1722.06.05/38.70,20.60	6.4/VIII	**8**	**1855.02.28/40.20,29.10**	**7.4/X**	N	1958.08.27/37.40,21.00	6.4/V
	1723.02.22/38.60,20.65	6.7/VIII		1855.07.03/41.90,19.60	6.5/IX		1959.09.01/40.81,19.80	6.4/VIII
E	1723.09.—/38.40,27.00	6.4/VIII	N	1858.02.21/37.87,22.88	6.5/X		1959.11.15/37.78,20.53	6.8/VII
4	**1754.09.02/40.60,30.00**	**7.2/X**		1859.08.21/40.10,26.00	6.9/IX		1960.05.26/40.63,20.65	6.5/VIII
N	1756.11.26/40.50,26.40	6.7/VII		1861.12.26/38.25,22.16	6.7/X	E	1964.10.06/40.10,27.93	6.9/IX
	1759.06.22/40.60,22.80	6.5/IX	E	1862.03.14/38.30,20.40	6.5/IX		1967.03.04/39.20,24.60	6.6/V
5	**1766.05.22/40.80,29.10**	**7.3/IX**		1862.11.03/38.50,27.90	6.9/X	**12**	**1967.07.22/40.60,30.80**	**7.2/IX**
N	1766.07.24/38.10,20,40	7.0/IX		1863.11.06/40.50,29.10	6.4/VIII	N	1968.02.19/39.50,25.00	7.1/IX
	1766.08.05/40.74,27.11	7.6/X		1864.06.14/40.30,25.10	7.0/VII	E	1969.03.28/38.29,28.57	6.6/VIII
			9	**1912.08.09/40.62,26.88**	**7.6/X**		1970.03.28/39.16,29.42	7.1/IX
			N	1915.01.27/38.36,20.60	6.6/IX		1972.05.04/35.10,23.60	6.5/V
				1915.08.07/38.50,20.62	6.7/IX		1975.03.27/40.40,26.10	6.6/VII
			E	1919.11.18/39.20,27.40	7.0/IX			

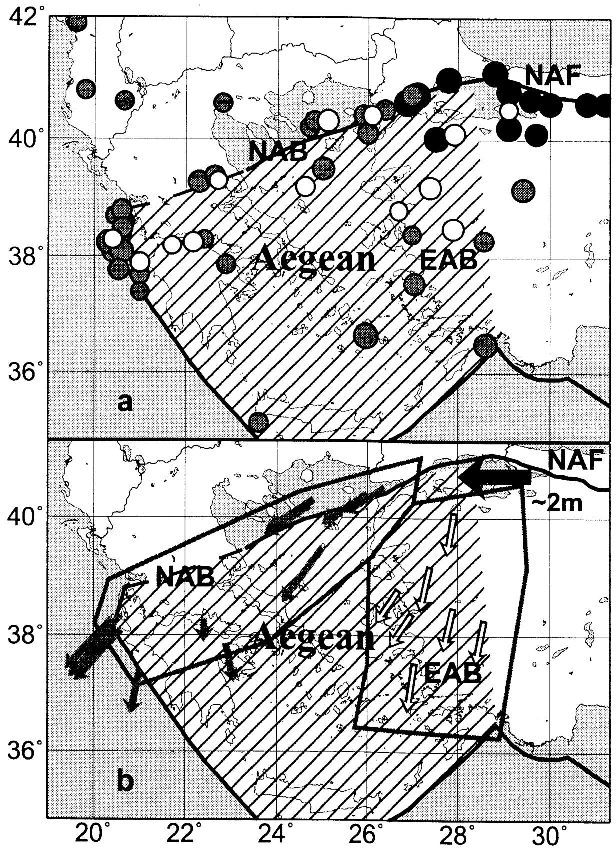

Figure 1. a)Epicenters (solid circles) of the major Marmara Sea earthquakes ($M \geq 7.0$) and strong Aegean earthquakes ($M \geq 6.4$) which followed within a period of 5 years (gray circles) or between 5 to 10 years (open circles). b) Slip vectors of the first strong ($M \geq 6.4$) earthquakes which occurred along the NAB (gray arrows) following the corresponding major ($M \geq 7.0$) Marmara earthquakes and along the EAB (open arrows) following the corresponding strong ($M \geq 6.7$) earthquakes in the NAB.

Figure (1a) shows a map of the epicenters listed in Table (1). Solid circles show the epicenters of the twelve major ($M \geq 7.0$) Marmara area earthquakes. The 10-year period following the Marmara events is separated in two equal 5-year intervals and gray or open circles denote strong ($M \geq 6.4$) Aegean mainshocks which occurred within the first 5 years or between 5 to 10 years, respectively. For the 46 strong shocks which followed the Marmara major earthquakes within a period of 10 years, 30 of them occurred along the NAB, 11 events occurred in the broad belt associated with the EAB, while only 5 shocks occurred outside these two belts. Therefore, during this post-mainshock interval of 120 years (12 sequences of 10 years) about 90% of the known strong Aegean earthquakes occurred in the NAB and EAB, which limits are also shown in Figure (1). Considering that in the remaining 378 years of the period 1500-1998 about 60% of the known strong mainshocks ($M \geq 6.4$) occurred in the NAB and EAB [*Papazachos and Papazachou,* 1997], we can conclude that for several years after the generation of the major earthquakes in the Marmara Sea area strong earthquake activity is mainly concentrated in these two seismic belts. This observation along with the fact that both NAB and EAB are spatially connected with the Marmara Sea seismic belt (see fig.1) further indicates that the generation of major earthquakes in the Marmara Sea area triggers strong earthquakes in NAB and EAB.

Information presented in Table (1) shows that all the 12 first strong shocks in the Aegean followed the corresponding major Marmara earthquakes within 3 years, while 11 of them occured along the NAB. The time gap between the each major Marmara earthquakes and its first postshock along the NAB shows that the rate of these postshocks between 0 to 3.2 yrs is about 3 times higher than its value after this period. Moreover, more then 60% of all the strong NAB events occur within this 3.2yr period, than the remaining 6.8yrs (3.2-

10years). On the other hand, strong seismicity along the EAB is almost uniformly distributed in the 5-year period after the first strong event in the NAB.

Tectonic Implications of Earthquake Triggering

Table (1) shows that for each major Marmara earthquake at least one postshock occurs along the NAB. The first such postshock (denoted by N in Table 1) has the highest probability to have been triggered by the corresponding Marmara earthquakes, since later postshocks along this boundary may be triggered by this first postshock. Similarly, the first postshock along the EAB (denoted by E in Table 1) has the highest probability to have been triggered by the preceding NAB postshock. Therefore, it is of interest to examine the focal mechanism of these first postshocks. For this reason, typical fault plane solutions which have been determined and apply for the seismogenic source where the epicenter of the corresponding shock is located were used, except for events after 1964 which are based on originally reported fault plane solutions [*Papazachos et al.,* 1998]. The horizontal projections of the slip vectors (scaled to the expected slip logarithm) are shown in Figure (1b), where gray and open vectors correspond to shocks along the NAB and EAB, respectively.

The twelve first postshocks along the NAB occurred within three years (mean value 1.37±0.91 yrs) after the generation of the corresponding major Marmara earthquakes, having a mean magnitude, $\bar{M}$=6.5±0.4. Ten of them occurred by strike slip faulting (five in the northern Aegean and five in the Ionian islands) and two by normal faulting (in central Greece). Figure (1b) shows that during the generation of these shocks, slip along the NAB is expressed by a movement of the southern fault block in a more or less southwest direction. Moreover, in 7 out of the 12 studied cases at least one posthock occurred in the EAB. The first such shock occurred within 1-5 years (mean value 2.92±1.24 years) after the occurrence of a strong ($M \geq 6.7$) postshock in the NAB. All seven shocks ($\bar{M}$=6.7±0.5) exhibit normal faulting with a strike slip component. Figure (1b) shows that during the generation of these shocks, fault-slip in the EAB occurs with movement of the southern fault block in a south/southwest direction.

The previous results suggest that coseismic slip (~2m) in the westernmost part of the Northern Anatolian Fault triggers a more or less southwestward movement of the Aegean plate. This movement is first expressed by the generation of strong earthquakes ($M \geq 6.4$) in the NAB within about 3 years after the coseismic slip along the NAF. Later, and within of 1 to 5 years after the generation of a strong earthquake ($M \geq 6.7$) in the NAB, strong earthquakes are often generated in the EAB.

Seismicity Level in NAB and EAB During the Excitation Periods

For a quantitative estimation of seismicity we relied only on the use of instrumental data (1911-1998) and estimated the parameters *a* and *b* of the Gutenberg-Richter frequency-magnitude relation [*Gutenberg and Richter,* 1944]. There are 4 postshock sequences during the instrumental period (No 9, 10, 11, 12). The frequency-magnitude relation was calculated for the strong mainshocks ($M \geq 6.0$) which occurred in the NAB during each of the 3-years postshock period (total period of 12 years), as well as for the remaining 76 years of the instrumental period (1911-1998), which have been considered to express the background seismicity. Both relations were reduced to a period of 100 years and plotted in Figure (2a) with the corresponding best-fit least squares' lines. The corresponding normalized parameters are a=7.01, b=0.82± 0.07 for postshocks along the NAB, and a=9.06, b=1.21±0.09 for background seismicity within the same belt. Using these values we find that during the 3-year postshock period the rate of shocks with $M \geq 6.0$ is doubled in the NAB and its ratio to the background rate increases with magnitude (see fig.2a).

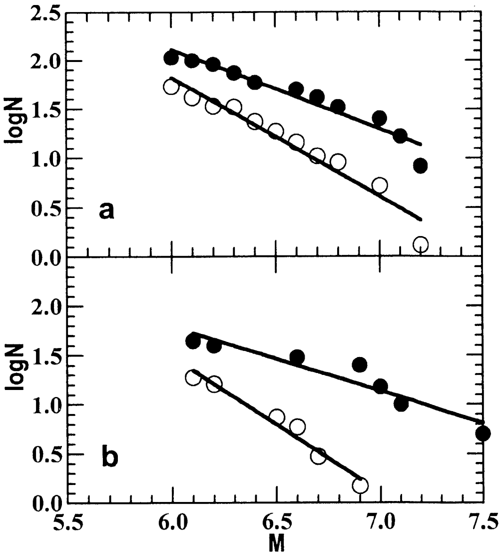

Figure 2. a)Frequency-magnitude relation for the NAB during the period of excitation (black circles) and of background seismicity (open circles). b) Same as (a) for the EAB.

Using the same procedure, the strong earthquake seismicity in the EAB during the five-year excitation period has also been examined, with respect to the corresponding background seismicity (Fig.2b). The corresponding values are a=5.70, b=0.65±0.08 for the excitation period, and a=9.78, b=1.38± 0.11 for the background seismicity. It is again evident that the seismicity rate of the earthquakes with $M \geq 6.0$ in the EAB is doubled during the examined five-year excitation period and the ratio of this rate to the corresponding background rate also increases with magnitude (see fig.2b). Examination of the post-1950 cases (No 10, 11, 12) for which the data are complete for $M \geq 4.5$, shows that the slope of the LogN-M data changes for $M<6.0$ in both NAB and EAB and the seismicity level remains higher for the excitation period, compared to background seismicity, up to the magnitude of 4.5-4.7. This indicates that the proposed triggering controls not only strong but also moderate (down to M=4.5) seismicity.

Discussion

Figure (2) shows that the increase of seismicity along the NAB during the 3 years following the major Marmara earthquakes and in the EAB during the 5-year period which follows the strong ($M \geq 6.7$) earthquakes in the NAB is mainly expressed by the increase of the average earthquake magnitude. This high strong-earthquake seismicity also results in the strong decrease of the b values (from 1.21 to 0.82 in the NAB and from 1.38 to 0.65 in the EAB) during both excitation periods with respect to the corresponding period of background seismicity, which indicates an increase of the tectonic stress [*Scholz,* 1968]. This observed decrease is significant, given the small b-value uncertainties compared to the large b-value change in both cases. These observations are in agreement with the tectonic process previously described, since a fast westward coseismic movement of the Anatolia plate is expected to cause stress accumulation in the NAB and the fast southwestward movement of the Aegean plate is expected to result in a stress increase in the EAB. Clearly this accumulation can not be explained in the context of elastic stress increase due to the Marmara events, which does not exceed 0.1bars for $M \sim 7.5$ events outside the Marmara bay area. Therefore, alternative models, possibly viscoelastic, are necessary in order to understand such long-range interactions.

It is reasonable to make the hypothesis that a similar triggering pattern is expected during the next years due to the generation of the major ($M=7.4$) destructive earthquake in northwestern Turkey (Izmit area) on 17 August 1999. Using the determined a and b values we find that the expected number of strong earthquakes ($M \geq 6.0$) along the northern boundary of the Aegean plate (northern Aegean-central Greece-Ionian islands) during the next 3 years is 3.7 with $\bar{M}=6.5 \pm 0.4$, corresponding to an annual probability of 71%, compared to the 47% predicted by the background seismicity. Moreover, the 5-years excitation period in the EAB is expected to start after the generation of the first strong ($M \geq 6.7$) earthquake in the NAB. The estimated a and b values suggest that approximately 3 such earthquakes with $\bar{M}=6.7 \pm 0.5$ are expected along the eastern boundary of the Aegean plate (Western Turkey, Greek islands of eastern Aegean) during this 5-year period, corresponding to an annual probability of 47%, compared to the background probability of 27%.

During the 3-year periods following the 12 major Marmara earthquakes the seismicity is very low in the remaining part of the Aegean area. Thus, along the outer Hellenic arc (south of Zante-Crete-Rhodes), where this seismicity is usually high, no known strong earthquake ($M \geq 6.4$) occurred during the examined time period with a total duration of 36 years (see Table 1). It is, therefore, expected that strong shallow earthquake seismicity will be at quiescence along the outer Hellenic arc during the next three years or so.

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