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Space–Time Migration of Earthquakes Along the North Anatolian Fault Zone and Seismic Gaps

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Abstract – The North Anatolian fault is a well-defined tectonic feature extending for 1400 km across Northern Turkey. The space–time distribution of seismicity and faulting of this zone has been examined with a particular emphasis on the identification of possible seismic gaps. Results suggest several conclusions with respect to the temporal and spatial distribution of seismicity. First, the earthquake activity appears not to be stationary over time. Periods of high activity in 1850–1900 and 1940 to the present bracket a period of relatively low activity in 1910–39. Second, there appears to have been a two-directional migration of earthquake epicenters away from a central region located at about 39°E longitude. The migration to the west has a higher velocity (> 50 km/yr) than the migration to the east (≤ 10km/yr). The faulting associated with successive earthquakes generally abuts the previous rupture. Some existing gaps were filled by later earthquakes.

At present there are two possible seismic gaps along the North Anatolian fault zone. One is at the western end of the fault, from about 29° to 30°E. Unless this is a region of ongoing aseismic creep, it could be the site of a magnitude 6 or greater earthquake. The other possible gap is at the eastern end, from about 42° to 43°E, to the west of the unexpected M = 7.3 event of 24 November 1976.

Key words: Earthquake prediction; Seismicity migration; Tectonics of Turkey.

Introduction

The North Anatolian fault zone is a major tectonic feature with a well-defined fault trace and an established history of seismicity (Allen, 1969, 1975; Ketin, 1968, 1976; Ambraseys, 1970; Seymen and Aydin, 1972; Sengor, 1978; Dewey, 1976). The fault trace is well defined along the 1000 km long central portion between longitudes 31° and 41°E. Farther eastward the extension of the fault is difficult to define uniquely although the 1976 earthquake (Toksöz *et al.*, 1977) identified a possible extension. To the west of 31°E longitude the fault appears to break into two, or possibly three, branches. In this region the earthquake mechanisms show a N–S tension component in addition to the dominant right-handed strike slip component (McKenzie, 1972). Most intermediate and large magnitude earthquakes occurring

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along the North Anatolian fault have produced surface breaks (AMBRASEYS and ZATOPEK, 1969; AMBRASEYS, 1970; ARPAT *et al.*, 1977; KETIN, 1976; TOKSÖZ *et al.*, 1977; WALLACE, 1968). Furthermore, because of topography and water resources, the fault zone is a relatively densely populated, agricultural area dotted by many villages and small towns. Even in times before seismographs existed, the fault dimensions could be estimated from geographic distribution of damage and isoseismals. In this study, we have examined the space–time distribution of earthquakes on the North Anatolian fault zone with a particular emphasis on seismicity gaps. Although we have examined historic catalogs, the primary data we analyzed in this study cover the period 1910–77. The earthquake catalogs for this period appear to be reasonably complete and field data are more readily available.

The previous studies (KETIN, 1959; DEWEY, 1976; ALLEN, 1975; AMBRASEYS and ZATOPEK, 1969; CANITEZ and TOKSÖZ, 1978) have noted the migration of the earthquake epicenters along the fault zone. Trends that were noticed included eastward migration, westward migration, and alternating occurrence of the earthquakes between the east and the west. DEWEY (1976) carried out an extensive study and identified a clear westward migration. He further sought some physical mechanism for such migration.

In this paper we look at both the eastward and westward trends of earthquake migration along the North Anatolian fault. There are indications of two possible gaps which require further study.

Seismicity of Turkey and the North Anatolian fault zone

The seismicity of Turkey is controlled by a complicated interaction of several plates (MCKENZIE, 1972). Figure 1 is a seismotectonic map showing some major fault zones and earthquake epicenters. In the southeast the Arabian plate collides against the Anatolian and Asian plates. In the southwest, the Mediterranean plate is subducting under the Anatolian and Aegean plates. In western Turkey, seismicity occurs along a series of east–west trending normal faults. This region consists of a series of horsts and grabens.

In the north, the North Anatolian fault zone is a major boundary between the Anatolian and Asian plates. The sense of the motion is right handed and the slip rate is relatively high, ranging from 3.2 to 11 cm/yr (BRUNE, 1968; NORTH, 1974). Our estimate of the slip rate is 6 cm/yr averaged for the period 1910–77, and 12 cm/yr for the period 1939–77.

The East Anatolian fault zone appears to be a left-handed conjugate fault to the North Anatolian fault (ARPAT and SAROGLU, 1972; MCKENZIE, 1972). It has a much lower slip rate (less than half of that of North Anatolian fault) and fewer earthquakes. The exact value of slip is difficult to calculate because of sparsity of events. Butting against East Anatolian fault from the south is the north–south trending rift zone

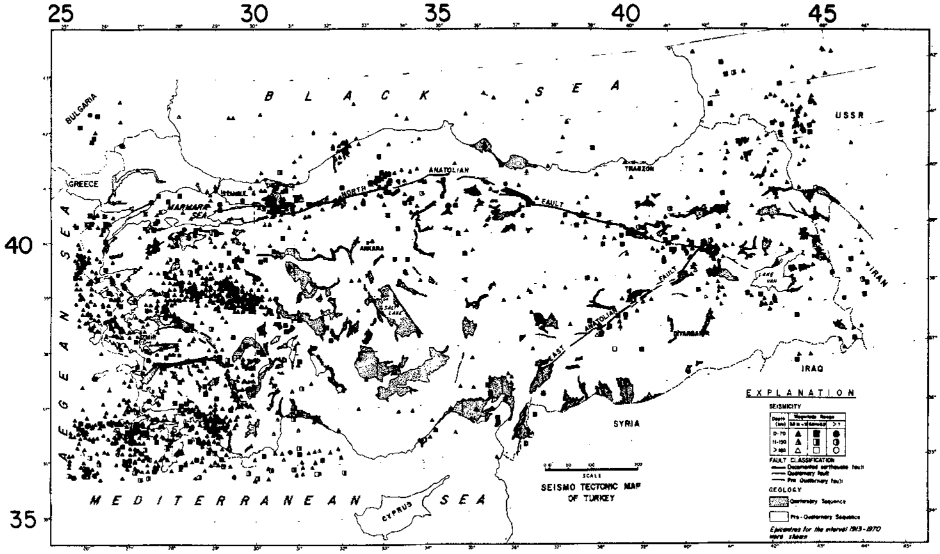

Figure 1
Seismotectonic map of Turkey showing earthquake epicenters and the major faults.

through Hatay and Maras. Although the tectonics of the whole region are complex, the North Anatolian fault zone can be distinguished as a separate feature, and the associated seismicity can be clearly identified. Thus, our present study is confined only to the North Anatolian fault zone.

In identifying the seismicity pattern of the region it is important to have data over as long a time period as possible. There are earthquake catalogs for Turkey dating back 2000 years (Ergin *et al.*, 1967). However, it is not clear how complete the list of historic earthquakes is and how accurate the intensities are. Generally, population distributions, education and political climate affect the historic data sets.

In this study we examined several catalogs: Ergin *et al.* (1967); Karnik (1968); Gutenberg and Richter (1949); Alsan *et al.* (1965) and the U.S.G.S.–N.E.I.S. catalogs. Looking at the seismicity and average seismic energy release per year, it is clear that the historic records are very incomplete until about the year 1500. For the following four hundred years, the data base improved. In Fig. 2, seismic energy release is plotted as a function of time. The energy E_s was calculated using the empirical relationship (Båth, 1973)

$$\log E_s = 12.24 + 1.44 \text{ M} \tag{1}$$

with intensity to magnitude conversions taken from the I.T.U. data (Ergin *et al.*, 1967), for the pre-instrumental period. The incompleteness of data is seen from a step jump in 1840 on the energy release curve shown in Fig. 2. After that period, the data base becomes more complete for western Turkey but not for eastern Turkey.

The reliable data base for the North Anatolian fault zone starts at about 1910.

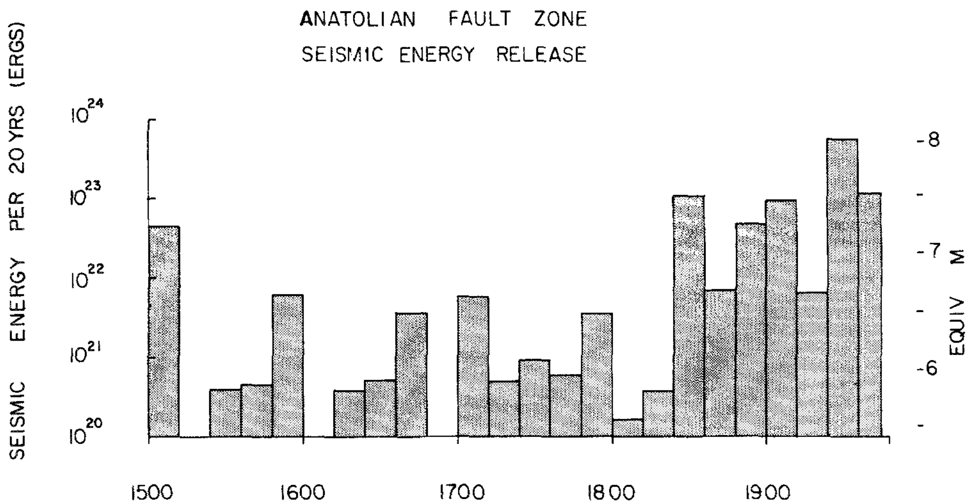

Figure 2
Seismic energy release along the Anatolian fault zone between 1500 and 1977, averaged over 20 year segments. Estimated energy is subject to errors in magnitude and intensity to energy conversion, and completeness of the catalogs for the historic data. The 26 December 1939 $M = 7.9$ event has been included as a 1940 event to more clearly show the low activity level of the preceding 20 years.

During this period the whole region was reasonably well populated. Both observers' descriptions of local effects and instrumental data are available for many events. In this study we limit our analysis to the period 1910–77.

The largest event in the seismic record is the M = 7.9 event of 26 December 1939. The 20 years prior to this event was a period of low activity. This is apparent in the energy release graph of Fig. 2 and also in Fig. 3, which shows the number of events in individual magnitude ranges. Although the estimation of a threshold of data completeness is difficult, ALSAN *et al.* (1975) suggest that the catalog is complete above M $\sim$ 5.5 for the entire 1913–70 interval, but there is no quantitative confirmation of this. The low number of M $\geq$ 6 events in the 20 or 30 years prior to the sequence of large events starting in 1939 is therefore probably real and may represent a quiescent period similar to those described by MOGI (1968).

Space-time migration of earthquakes

The North Anatolian fault zone is basically a linear feature with a small curvature in the middle. Thus the spatial distribution of seismicity can be analyzed as an east–west one-dimensional model. In this study we investigate the space–time distribution of the earthquakes along the trend of the fault in a manner similar to that of DEWEY (1976). Since the record of small earthquakes is not complete, we include only earthquakes of $M_s \geq 5.9$ (intensity $\geq$ VII). These are listed in Table 1.

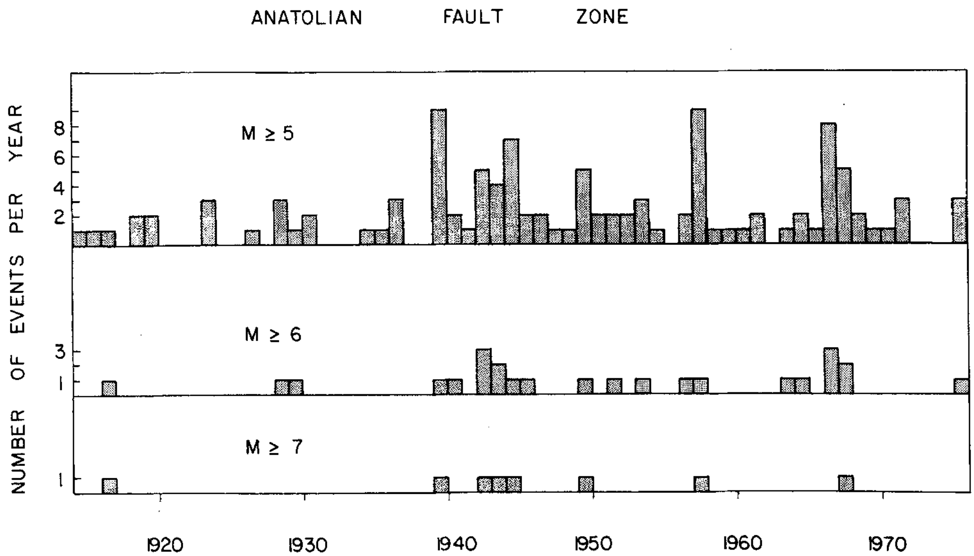

Figure 3
Number of earthquakes per year with magnitudes M ≥ 5, 6 and 7 in the 1913–75 time period.

In Fig. 4, the distribution of epicenters along the east–west trend of the fault versus time is shown. There appear to be two trends, one to the west with an average slope of 0.02 yr/km and another to the east with 0.1 yr/km. It is clear that the westward migration is faster immediately after the 1939 earthquake and slows down after 1945. The average velocities are about 50 km/yr to the west and 10 km/yr for eastward migration when averaged over a 38-year time span.

A better illustration of the migrations and their relevance to seismic gaps can be illustrated by plotting the length of observed surface faulting for each earthquake. In most cases there are surface breaks associated with earthquakes. For the larger events these have been mapped. For other events the length of the highest intensity contour gives some measure of the fault length. We have used these criteria to plot fault length vs. magnitude for the North Anatolian fault zone earthquakes (Fig. 5). Fault length data are tabulated in Table 1. An empirical equation fitting these data gives

$$\log L = 0.78 \, M_s - 3.62 \qquad (2)$$

where L = fault length, M_s = surface wave magnitude. This relationship is similar to those obtained for California earthquakes (SMITH and VAN DE LINDT, 1969; CANITEZ and TOKSÖZ, 1978). When information for actual surface breaks was not available, we used equation (2) to estimate the fault lengths.

The distribution of surface faulting is shown on the maps in Figs. 6a,b,c for three different periods. In these and subsequent figures, fault breaks are plotted as they were mapped in the field, when such information was available. In other cases damage scales and isoseismals were used to fix the fault trace. (ERGIN *et al.* (1967) give a brief

Table 1

List of earthquakes used in this study (data from ALSAN (1976), *except as noted)*

Number	Yr	Date Mth	Date Day	Time Hr:Min	Epicenter Lat	Epicenter Lon	M	Fault length
1	1910	6	25	19:26	41.00	34.00	6.2	
2	1916	1	24	6:56	40.27	36.83	7.1	
3	1923	4	29	9:58	40.07	36.43	5.9	
4†)	1924	9	13	14:35	39.96	41.94	6.8	
5†)	1928	5	2	21:57	39.64	29.14	6.5	
6	1929	5	18	6:42	40.20	37.90	6.5	
7†)	1934	11	27		37.90	40.20	6.0	
8	1939	11	21	8:49	39.82	39.71	5.9	
9	1939	12	26	23:59	39.80	39.51	7.9	350
10	1941	11	12	10:09	39.74	39.43	5.9	
11	1942	12	11	02:40	40.76	34.83	6.1	
12	1942	12	20	14:03	40.87	36.47	7.0	50
13	1943	6	20	15:37	40.85	30.51	6.6	30
14	1943	11	26	22:24	41.05	33.72	7.4	280
15††)	1944	2	1	3:25	40.8	32.2	7.3	160
16	1945	10	26	13:56	40.90	33.29	6.0	45*)
17	1946	5	31	3:12	39.29	41.21	5.9	
18	1949	8	17		39.54	40.57	6.8	75
19	1951	8	13	18:36	40.88	32.87	6.9	60*)
20	1953	9	7	3:59	41.09	33.01	6.4	60*)
21	1954	10	24		40.00	40.00	6.0	
22†)	1956	2	20	20:35	39.89	30.49	6.4	
23†)	1957	5	26	6:36	40.67	31.00	7.1	50*)
24	1957	5	26	9:39	40.76	30.81	5.9	
25	1960	1	26	9:53	40.19	38.75	5.9	
26	1963	9	18	16:59	40.77	29.12	6.3	35*)
27**)	1964	6	14	12:18	38.13	38.51	6.0	40*)
28	1964	10	6	14:33	40.30	28.23	7.0	60*)
29	1966	8	19	12:23	39.17	41.56	6.7	20
30	1966	8	20	12:05	39.16	40.70	6.1	
31	1967	7	22	16:56	40.67	30.69	7.2	
32	1967	7	26	18:53	39.54	40.33	6.2	
33	1968	9	3	8:24	41.31	32.39	6.5	
34	1976	11	24	12:22	39.10	44.02	7.3	50

*) Designates fault length estimated from isoseismals.
**) Designates event on East Anatolian fault.
†) Designates event probably not related to North Anatolian fault.
††) Epicenter from macroseismic data (ERGIN *et al.*, 1967).

description of these.) For smaller events, where neither of these data are generally available, the surface break is assumed to be parallel to the main fault zone with the epicenter in the middle. Since the fault length of these events is generally small ($\sim$20 km), any error that may be introduced is small.

In Figs. 6a,b,c the time periods covered are 1910–37, 1938–77 and 1910–77,

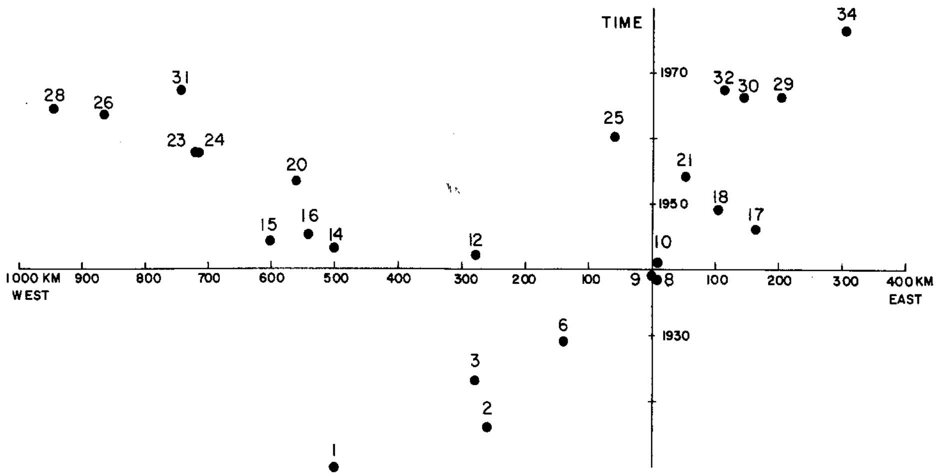

Figure 4
Time–space distribution of earthquake epicenters along the North Anatolian fault zone in the period 1910–77. The origin corresponds to year 1940, and the epicenter (39.8°N and 39.7°E) of the 26 December 1939 earthquake. Numbers identifying earthquakes are the same as those given in Table 1.

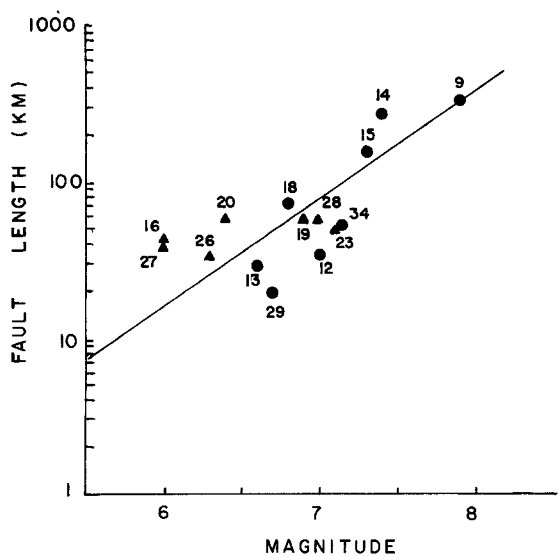

Figure 5
Fault length vs. magnitude for events of the Anatolian fault system, including fault length estimates from field studies (circles) and estimates from isoseismals (triangles). The line through these points ($\log L = 0.78\ \mathrm{M} - 3.62$) is only slightly different from the relationship found for California earthquakes ($\log L = 0.59\ \mathrm{M} - 2.24$) by SMITH and VAN DE LINDT (1969).

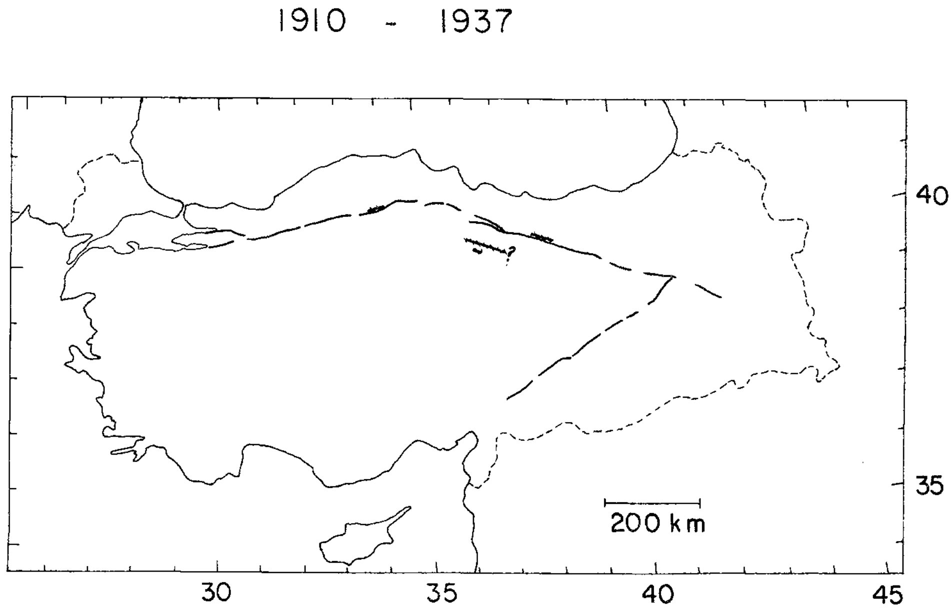

Figure 6a

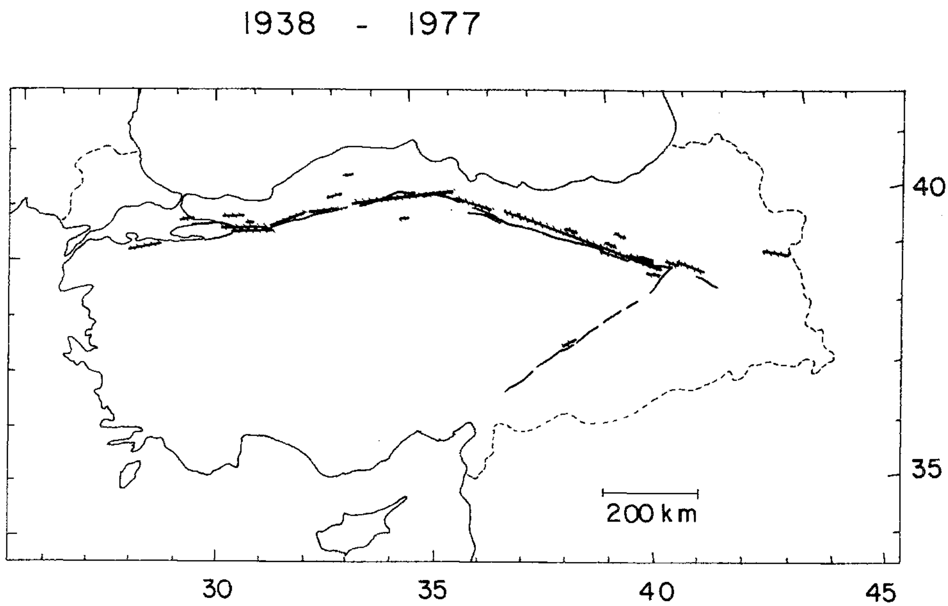

Figure 6b

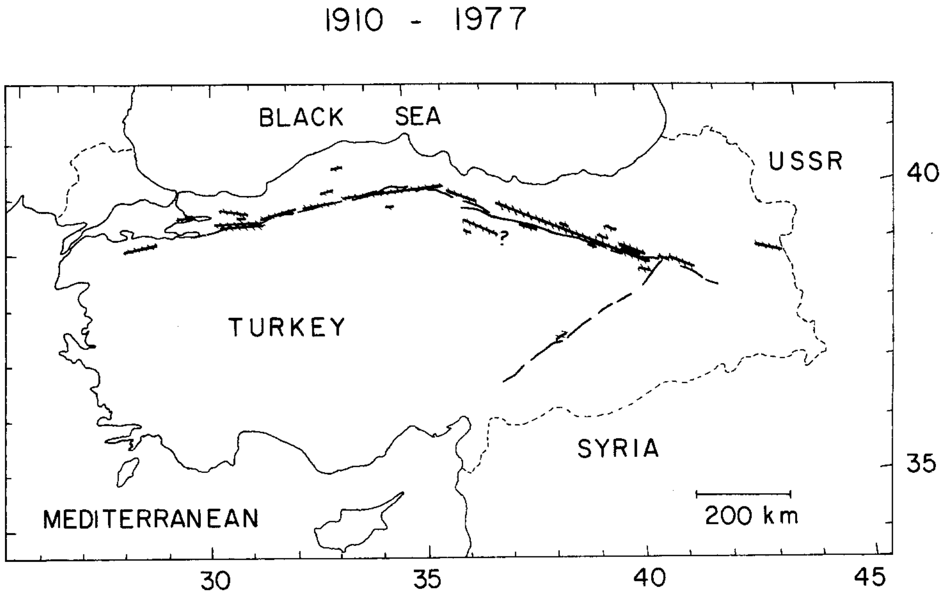

Figure 6c
Earthquake fault breaks along the North Anatolian fault zone. Fault trace is shown as a slight line, fault ruptures as heavy straight hatched lines. Three figures correspond to three time periods: (6a) 1910–1937; (6b) 1938–1977; (6c) 1910–1977.

respectively. As seen in Fig. 3 and in Table 1, there were relatively few large events between 1910 and 1938. The largest earthquake in recent history (M = 7.9) occurred on 26 December 1939. This appears to have been the first in a series of intermediate and large earthquakes. The fault breaks associated with these events cover almost 1500 km along the North Anatolian fault zone. There are very few gaps and relatively little overlap.

The same phenomenon is better illustrated in the simplified diagram in Fig. 7. Fault breaks are plotted along an east–west line as a function of time. Starting with the 1939 (M = 7.9) event there is a very rapid propagation of earthquakes to the west. In three successive events, rupture occurs along about a 500 km segment of the fault (velocity ~100 km/yr.) Afterward there is a continued progression westward, but at a slower rate. There seems to be a filling of a gap at 31°E longitude by earthquakes number 23 and number 24 occurring 13 years after event number 15 (Fig. 7, Table 1). There is a 60 km gap at about 30°E longitude. This will be discussed later and we consider it a potential site for monitoring. It is not clear whether the small gap at 36°E is real or due to the inaccuracy in mapping of fractures of events 12 and 14.

The progression of the earthquakes eastward from $\lambda = 40°E$ appears to be at a much slower rate (about 10 km/yr). Complete rupture had occurred between $\lambda =$ 40°–42°E in about 30 years. Then, there was a quiescent period until 24 November

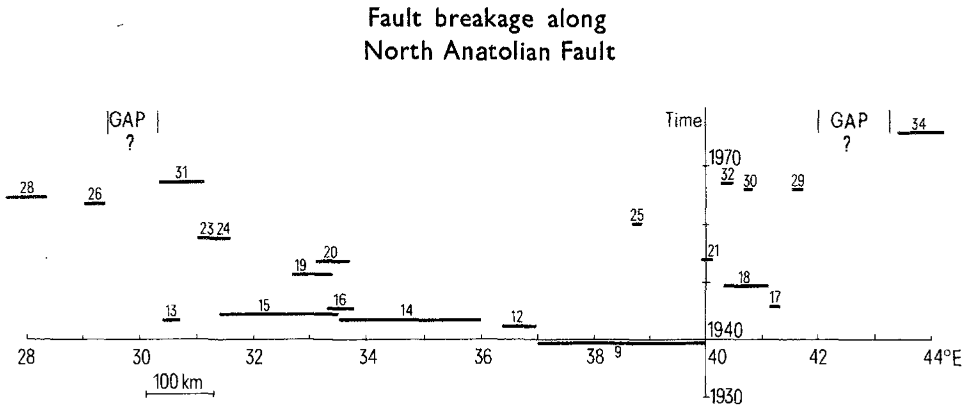

Figure 7
Space–time distribution of earthquake faulting along the North Anatolian fault zone. Fault breaks are projected along an east–west line. Length of each line corresponds to the length of the observed break or the length estimated using equation 2. The earthquakes are identified by the numbers listed in Table 1. Note the two possible gaps near the eastern and western end of the diagram.

1976, when a magnitude $M_s = 7.3$ earthquake occurred further east. The location of this event (see Fig. 6) is somewhat displaced to the north from a linear extrapolation of the North Anatolian fault zone. However, the right-handed strike-slip faulting is consistent with the North Anatolian events (TOKSÖZ *et al.*, 1977; ARPAT *et al.*, 1977). Thus on the eastern side, the North Anatolian fault may have been segmented northward through a set of en-echelon steps. Recent mapping has indicated the presence of geologically active strike-slip faults to the west of the 1976 earthquake. Thus the region between $\lambda = 42°$–$43°$E longitude probably represents another seismic gap.

This region of Eastern Turkey had been characterized as a zone of convergence and N–S shortening by MCKENZIE (1972). However, neither the 1976 earthquake nor the local geology characterized by strike-slip and, possibly, normal faults supports this interpretation. The local tectonics of the region are complicated and more work needs to be done before the seismicity patterns can be defined.

Discussion of possible seismic gaps

Our study of the distribution of earthquakes and surface breaks is based primarily on local observations. However, because of the uniformity of the mechanisms and simplicity of tectonics of the North Anatolian fault zone, it is feasible to combine teleseismic information and field observations to understand the space–time distributions of earthquakes.

The general patterns of the seismicity include:

1. Earthquake occurrences are not stationary over time. There has been relatively high activity between 1850–1900, a quiet period from 1910–39 and an active period from 1940 to the present.

2. There appears to be a two-direction migration of earthquake epicenters from a central region located at about $\lambda = 39°$ longitude. The westward migration is faster (50 km/yr). This is very similar to the 80 km/yr velocity obtained by Dewey (1976). Eastward migration is slower.

3. The faulting associated with successive earthquakes generally seems to start from where the previous rupture has ended. Some existing gaps have been filled by later earthquakes.

4. At present there are two possible earthquake gaps on the North Anatolian fault zone. The gap in the west between 29° and 30°E longitudes is shown in more detail in Fig. 8. There have been two large earthquakes to the east and west of this gap in 1963 and 1967. The mechanism of the 1967 earthquake is right-handed strike-slip. The fault plane solution of the 1963 earthquake is not well defined. The strike is close to east–west and the dip is steep (McKenzie, 1972). The slip has both right-handed

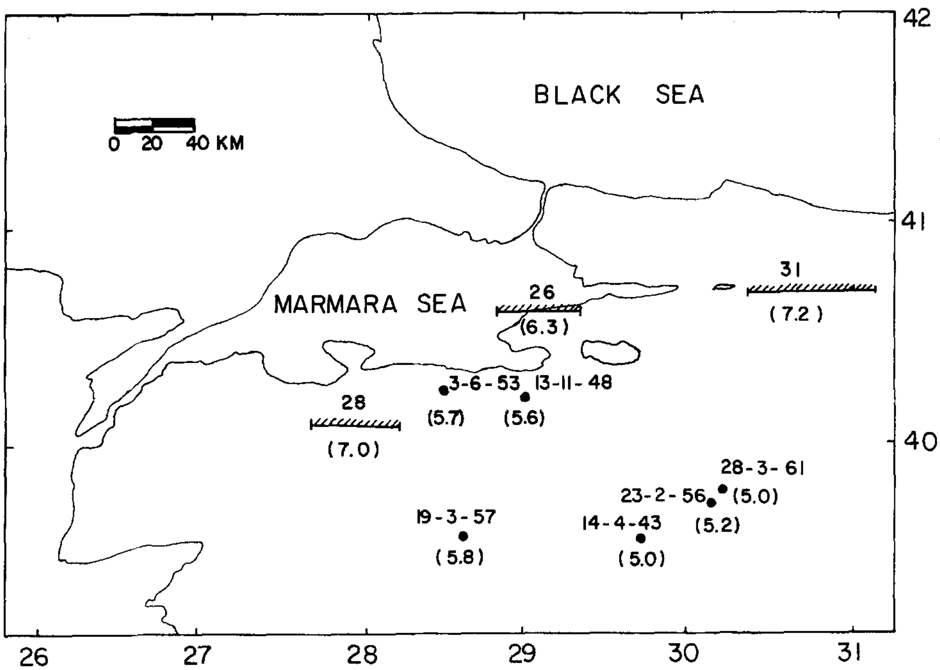

Figure 8

Earthquake epicenters and observed faulting along the west end of the North Anatolian fault zone. Note the possible gap to the west of the 22 July 1967 earthquake (number 31) fault break. It is not known whether aseismic slip occurs in this area, or if this is a locked zone and a possible site of a future earthquake.

strike-slip and dip-slip components. Surface geology suggests two parallel fault traces in the gap region, each extending east from the two fingers of the Sea of Marmara. Neither the local reports nor seismicity catalogs indicate earthquakes of $M \geq 5.0$ in this area. Unless this zone is deforming by creep or some other aseismic means, it should be considered a gap with a potential earthquake of magnitude greater than 6.

The second gap is along the eastern side of the North Anatolian fault zone between 42° and 43°E longitudes. The importance of this zone really emerged after the 24 November 1976 earthquake ($M_s = 7.3$) in an unsuspected area. There is no uniformity of opinion on the eastward extension of the North Anatolian fault zone. The 1976 earthquake seems to indicate a possible northward translation of the fault zone. If this indeed is the case then the identified gap is a major one. Only recently geologically active faults have been mapped in this area. In eastern Turkey, the fault lengths corresponding to the magnitude of the events appear to be short $L \approx 20$ km for the 1966 Varto earthquake with $M_s = 6.7$ (WALLACE, 1968) and $L = 55$ km for the Van earthquake of 1976 with $M_s = 7.3$ (TOKSÖZ *et al.*, 1977). Thus the dimensions of the gap have the potential for a large earthquake ($M \geq 7$) in this area. However, because of the limited knowledge of geology, tectonics and seismicity of this area, this should be considered a speculative assessment.

It is necessary to undertake some detailed studies to determine whether these sites are indeed seismicity gaps. Monitoring of microseismicity, looking for evidence of creep or aseismic strain release, a very careful analysis of local earthquake catalogs and interviews with people to determine the existence or lack of earthquakes in these 'gaps' are necessary.

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