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Large spatial dispersion of the main shock epicenter of the 1944 Gerede earthquake (NW Anatolia, Turkey): A fault-triggering mechanism?

1944 Gerede depreminin (KB Anadolu, Türkiye) ana sarsıntı merkezüstünün geniş mekansal dağılımı: Bir fay tetikleme mekanizması?

M. Tekin YÜRÜR
Hacettepe Üniversitesi, Jeoloji Mühendisliği Bölümü, 06532 Beytepe, ANKARA

ABSTRACT

A large earthquake (M=7.2 according to the records of the Kandilli observatory) occurred along the N79°E-trending dextral transcurrent North Anatolian Fault (NAF) zone, near the Gerede town, in NW Anatolia, on 1 February 1944. Its epicenter is determined at three different areas. One of the epicenters corresponds to the Gerede macroseismic epicenter where N75°E-trending dextral surface ruptures are observed. The third aftershock (M=5.3) occurred near one of the other two epicenters located about 80 km far from the Gerede epicenter. The focal mechanism of the earthquake suggests a dextral transpressional fault plane with a direction (N52°E) and kinematics not compatible with the transcurrent NAF. This data set suggest that the Gerede earthquake may be triggered by a first movement on a fault zone associated with one or two of the epicenters other than the Gerede epicenter, followed by the immediately release of the elastic energy stored along the Gerede segment of the NAF. Topographic, geologic and seismic data indicated that the Karabük fault zone located at the north of the NAF zone may have played this role. The data of Bartın earthquake of 1968 confirm that the crust of the Pontide block, which is located between the NAF and the northern Black Sea and includes the Karabük zone deforms by shortening. This shortening is accommodated by simple shear deformation along the NAF and pure shear deformation at the Black Sea margin, and possibly by oblique faulting in the internal parts of the Pontide block.

Key words: Earthquake triggering, Gerede, North Anatolian Fault Zone, Turkey.

ÖZ

1 Şubat 1944'de, sağ yönlü doğrultu atımlı Kuzey Anadolu Fay (KAF) zonu boyunca ve Gerede yakınında şiddetli (M=7.2, Kandilli Rasathanesi kayıtlarına göre) bir deprem meydana gelmiştir. Depremin merkezüstü üç değişik yerde saptanmıştır. Bu yerlerden biri, sağ yönlü atımlar gösteren deprem kırıklarının oluştuğu Gerede'dir. Üçüncü artçı sarsıntı (M=5.3) Gerede merkezüstüne yaklaşık 80 km uzaklıkta bulunan diğer iki merkezüstünden birine yakın bir yerde yeralmıştır. Odak çözümü KAF'ın doğrultusu ve doğrultu atımlı hareketleri ile uyuşmayan bir sağ yönlü fay düzlemine işaret etmektedir. Bu veri kümesi, Gerede depreminin Gerede merkezüstü dışındaki diğer iki merkezüstünden birisi veya ikisine bağlı fay zonlarındaki bir ilk hareketin, KAF zonunun üzerinde elastik enerjinin toplandığı Gerede segmentini tetikleyebileceğini göstermektedir. Topoğrafik, jeolojik ve sismik veriler, KAF zonunun kuzeyinde yeralan Karabük fay zonunun böyle bir rolü üstlenmiş olabileceğini desteklemektedir. 1968 Bartın depremi verileri, KAF ile kuzeydeki Karadeniz arasında kalan ve Karabük fayını da içeren Pontid blokunun sıkışmakta olduğunu göstermektedir. Bu sıkışma, KAF boyunca basit makaslama, Karadeniz kenarında saf makaslama, Pontid blokunun iç kesimlerinde ise olasılıkla verev atımlı faylanma deformasyonları ile karşılanmaktadır.

***Anahtar kelimeler**: Deprem tetiklenmesi, Gerede, Kuzey Anadolu Fay Zonu, Türkiye.*

T. Yürür
e-mail: tyurur@hacettepe.edu.tr

INTRODUCTION

The North Anatolian Fault (NAF) is an important fracture zone of dextral strike-slip fault character, in Anatolia (Ketin, 1969; McKenzie, 1972; Şengör, 1984; Barka, 1992; Şaroğlu, 1988). The locally N79° trending fault zone generated a large earthquake (M=7.4: Ergin et al., 1967; M=7.2: KOERI, 2003), on 1 February 1944, near the Gerede town of the Bolu Province (Figure 1). N75°E-trending ground ruptures with dextral horizontal displacements up to 3 m and vertical offsets reaching 1 m are observed near the Gerede macroseismic epicenter (Eyidoğan et al., 1991). There are three different locations proposed for the epicenter, one near Gerede (Gencoğlu et al., 1990), and the others at approximately north (Ergin et al., 1967: epicenter E in Figure 1) and NNE (KOERI, 2003: epicenter K in Figure 1) of the Gerede epicenter (Figure 1a, seismic parameters given in Table 1). The Gerede location corresponds to the macroseismic epicenter, and one may think that the two others are erroneously located. This is possible since the epicentral determinations undertaken in that period may involve uncertainties reaching 50 km. First, the two epicenters are distant from the Gerede epicenter for about 80 km, a distance that fairly exceeds the maximum uncertainty limit. Thus one or two of the epicenters may have a significance besides the Gerede epicenter. Furthermore, the close location of the third aftershock near the epicenter K renders this problem more complex. On the other hand, the P wave first-arrival focal mechanism (see Figure 1b) suggests a dextral fault plane solution (Eyidoğan et al., 1991) with characteristics different than those expected for the NAF orientation and kinematics. In fact, the focal mechanism indicates a fault trending N52°E (FP1 in Figure 1b) instead of the N75°E direction of the ground rupturing, and a surface dipping 60° NW with a ra-

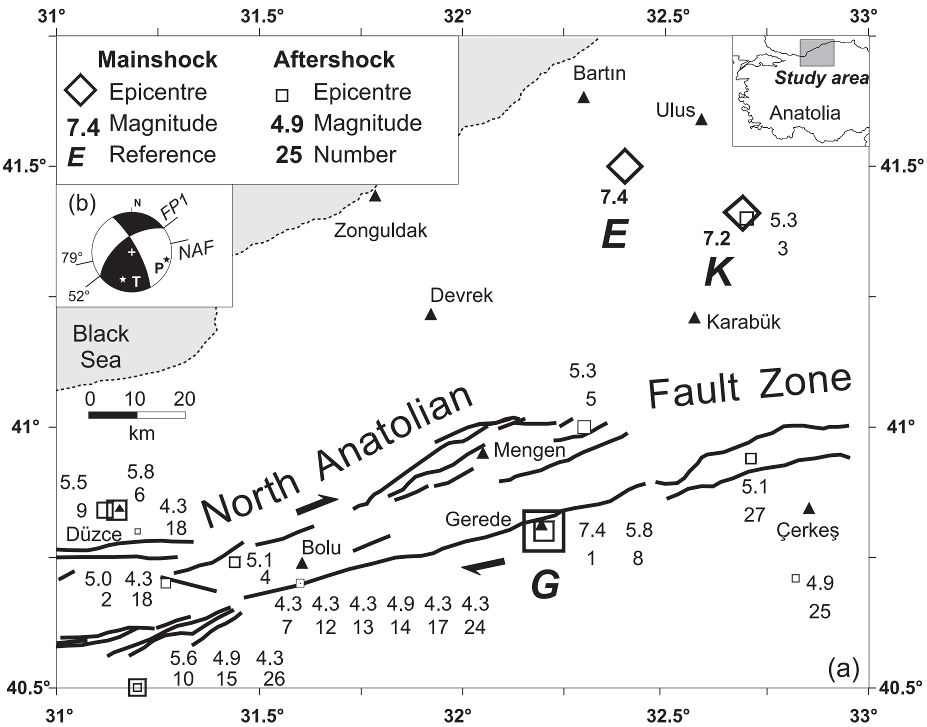

Figure 1. (a) Map showing the epicenters and aftershocks of the February 1, 1944 earthquake (References for the epicenter data: E: International Seismological Summary, Edinburg, ISS, *in* Eyidoğan et al., 1991); K: KOERI (2003); G: Gencoğlu et al. (1990). Fault zones drawn from the 1/500.000 geological map (Zonguldak sheet, MTA) (b) focal solution of the earthquake (Canıtez and Büyükaşıkoğlu, 1984 *in* Eyidoğan et al., 1991)).

Şekil 1. (a) 1 Şubat 1944 depreminin merkezüstü ve artçı sarsıntılarını gösteren harita (merkezüstü verilerinin kaynakları: E: International Seismological Summary, Edinburg, ISS, Eyidoğan vd., 1991'den; K: KOERI (2003); G: Gencoğlu vd. (1990). Fay zonları 1/500.000 ölçekli jeolojik haritadan çizilmiştir (Zonguldak paftası, MTA)). (b) depremin odak çözümü (Canıtez and Büyükaşıkoğlu, 1984, Eyidoğan vd., 1991'den).

Table 1. Parameters of the seismic data used in this study (Reference numbers : (1) Eyidoğan et al. (1991); (2) KOERI (2003); (3) Gencoğlu et al. (1990); (4) Alptekin et al. (1986); (5) USGS -NEIC (2003)).

Çizelge 1. Bu çalışmada kullanılan sismik verilerin parametreleri (Referans numaraları: (1) Eyidoğan vd. (1991); (2) KOERI (2003); (3) Gencoğlu vd. (1990); (4) Alptekin vd. (1986); (5) USGS-NEIC (2003)).

Ref.	Date	Time (°N)	Lat. (°E)	Lon.	Mag. (km)	Depth
1	01.02.1944	03:22:38	41.5	32.4	7.4	?
2	01.02.1944	03:22:39.9	41.41	32.69	7.2	10
3	01.02.1944	03:22:40	40.8	32.2	7.4	?
3	01.02.1944	06:08:52	40.7	31.27	5	10
3	01.02.1944	21:24	41.4	32.7	5.3	10
3	02.02.1944	03:33:17	40.74	31.44	5.1	40
3	10.02.1944	12:05:27	41	32.3	5.3	10
3	15.02.1944	?	40.84	31.15	5.8	?
3	20.02.1944	21:55:00	40.7	31.6	4.3	?
3	11.03.1944	?	40.8	32.2	5.8	?
3	05.04.1944	04:40:43	40.84	31.12	5.5	10
3	15.04.1944	04:10:00	40.5	31.2	5.6	?
3	18.10.1944	12:54:05	40.89	33.47	5.2	10
3	15.11.1944	22:55:00	40.7	31.6	4.3	?
3	18.11.1944	13:30:00	40.7	31.6	4.3	?
3	08.02.1945	06:24:00	40.7	31.6	4.9	?
3	09.02.1945	02:28	40.5	31.2	4.9	?
3	02.03.1945	10:39:44	41.2	33.4	5.6	10
3	24.03.1945	20:51:00	40.7	31.6	4.3	?
3	15.05.1945	00:57:00	40.8	31.2	4.3	?
3	07.06.1945	01:20:41	41.17	33.25	5.2	10
3	26.10.1945	13:56:51	41.54	33.29	5.7	50
3	20.11.1945	06:28:00	39.9	31.4	5.5	?
3	26.11.1945	13:56:40	41.5	33.5	5	?
3	21.01.1946	11:25:32	41.05	33.48	5	60
3	15.03.1947	00:57:00	40.7	31.6	4.3	?
3	19.05.1947	18:25:00	40.7	31.6	4.6	?
3	28.05.1947	14:58:00	40.7	31.6	4.3	?
3	19.12.1947	17:31:18	40.71	32.82	4.9	10
3	05.03.1948	08:10:00	40.7	31.6	4.3	?
3	24.12.1948	01:27:00	40.5	31.2	4.3	?
3	13.05.1949	20:14:07	40.94	32.71	5.1	20
3	08.11.1949	15:48:00	40.98	30.74	4.7	10
1	13.08.1951	18:33:30	40.8	33.4	6.9	10
4	03.09.1968	08:19:52.6	41.81	32.39	6.5	5
5	12.11.1999	16:57:19:55	40.758	31.161	Mw7.1	19

Ref.: Reference; Lat.: Latitude; Lon.: Longitude; Mag.: Magnitude.

ke of 16° for the direction of the motion, corresponding to transpressional oblique faulting. These dip and rake angles of the earthquake are also in contrast with the generally high dip angle and low rake values obtained from major NAF earthquake mechanisms (see the fault plane parameters given in Table 2).

This large dispersion of the location of the epicenters, and the discrepancy between the geometric characteristics of the surface ruptures and the fault plane solution may be related to seismologic problems. As already mentioned, the distances that separate the epicentral locations are exceeding the error limit of about 30 km. This means that the epicenter locations other than Gerede may have chances to be true. Consequently, if the spatial dispersion of the main shocks is true then the epicentral and kinematic differences between the instrumental and field data has to be explained. The close location of the third aftershock to the epicenter K (see Figure 1a) suggests that besides the Gerede epicenter, at least the epicenter K also intervened in the seismic event. In this study, a possible seismic scenario is considered, with a first assumption that all the epicentral data are true. In the next step, it may be speculated that the earthqu-

Table 2. Source parameters of the earthquakes mentioned in this study (Data sources : for Gerede (Ge) and Kurşunlu (Ku) earthquakes : Eyidoğan et al. (1991); Bartın (Ba) earthquake : Alptekin et al. (1986); Düzce (Ka) earthquake : USGS-NEIC (2003)).

Çizelge 2. Bu çalışmada ele alınan depremlerin odak çözüm parametreleri (Veri kaynakları : Gerede (Ge) ve Kurşunlu (Ku) depremleri : Eyidoğan vd. (1991); Bartın (Ba) depremi : Alptekin vd. (1986); Düzce (Ka) depremi : USGS-NEIC (2003)).

Name	Nodal Plane 1			Nodal Plane 2			P axis		N axis		T axis	
	Azi.	Dip	Rake	Azi.	Dip	Rake	Azi.	Plu.	Azi.	Plu.	Azi.	Plu.
Ge	332	77	31	232	60	164	101	12	351	57	198	30
Ku	348	83	–20	81	70	–172	303	18	150	69	36	9
Ba	28	38	80	222	52	99	306	6	37	5	172	82
Ka	269	73	177	359	88	17	133	10	7	73	225	14

Azi.: Azimuth; Plu.: Plunge.

ake first originated in a place beneath one (or two?) of the two other epicenters, and that this first motion has triggered the earthquake along the Gerede segment of the NAF zone, along which stresses equivalent to create a horizontal strain of about 3 m were already accumulated. It remains to investigate if the two other epicentral areas are able to generate seismic activities along fracture zones with constraints determined by seismic data. Topographic and geologic data are used to check this possibility. To verify if the faulting kinematics suggested by this analysis is compatible with the regional tectonics, data obtained from another earthquake, the 1968 Bartın earthquake (M=6.5, Alptekin et al., 1986) is used. The locations of the two other epicenters remain in the area between the Bartın and Gerede epicenters, so that the stress patterns associated with the Bartın event and the NAF zone can be interpolated for the fault zone supposed to trigger the 1944 earthquake. Focal mechanisms of two other regional large earthquakes of the NAF, namely the 1951 Kurşunlu and the 1999 Düzce earthquakes, are considered as examples to constrain the NAF stress pattern. The topographic, geologic and seismic data are presented in the following paragraphs to consider these points.

CHARACTERISTICS OF THE 1944 SEISMIC ACTIVITY NEAR GEREDE

The 1 February 1944 earthquake caused damage particularly in and near the Gerede town. Surface faulting observed in this zone justifies the location of one of the instrumental epicentral locations (see Figure 1). For the same earthquake, two other epicenters are determined, at the north and NNE of the Gerede epicenter. They are far about 80 km with respect to the Gerede epicenter. The location of the western epicenter is cited by Ergin et al. (1967) and Eyidoğan et al. (1991), while the eastern one is located based on data released by the Kandilli Observatory of Turkey (KOERI, 2003). The aftershocks are drawn based on data from the catalogue of Gencoğlu et al. (1990). The aftershock activity presents peculiar characteristics. After the first aftershock that was very close to the Gerede epicenter, the second shock took place along the NAF, at the west of Gerede. The third quake occurred very close to the epicenter determined by the Kandilli Observatory, hereafter designated as epicenter K. Again, the forth quake shook the NAF zone, but the following occurred in a place situated between the Gerede epicenter and the epicenter K. The oscillation of the first aftershocks near or between the two different epicenters proposed for the same earthquake suggests that both epicenters have played roles during the earthquake. As already expressed, the Gerede epicenter has a more precise role since it also corresponds to the macroseismic epicenter. A possible scenario, in which the Gerede and the epicenter K locations intervene together, is the one where stresses accumulated in one of the epicenters generate an earthquake whose rupture would trigger the other earthquake. Such a scenario may be accomplished in a relatively short time to remain undetected by the recording systems. The question is which one of the two epicenters was active first. It is possible to give an answer when considering the earthquake mechanism (see Figure 1b). Between the fault planes suggested by the focal solution, the dextral fault plane (see FP1 in Figure 1b) has a

N52°E trend with a 60°NW dip. This trend is in contrast with the local NAF direction (N79°E) and the orientation of the N75°E surface ruptures. Seemingly, the fault plane solution and the field data obtained from Gerede do not fit. It remains to check if the epicenter K is close to a fracture zone with characteristics satisfying better the fault plane solution. In the following paragraphs, this point is discussed.

SEISMIC DATA VERSUS GEOLOGY

To see the possible relationship between the epicenter K and a fracture zone, the 1944 data are plotted on a regional geological map (the 1/500.000 scaled Zonguldak sheet, MTA; the 1/2.000.000 scaled geology map of Turkey; MTA, 1989) (Figure 2). Both the two northern epicenters are close to mapped faults (WF: Western Fault and EF: Eastern Fault in Figure 2) with trends similar to the FP1. The EF is a thrust fault (the Karabük line of Blumenthal, 1948; the Zonguldak sheet, MTA; Tüysüz, 1993) but the WF is shown as a possible fault zone in the Zonguldak map. When considering the locations of the epicenters with respect to the fault traces, it may be thought that the EF or the Karabük fault has a NW-facing dip and the WF, a SE-facing dip. These fault planes are in agreement with the contractional character of the tectonics of the area as suggested by the Karabük fault kinematics, and both epicenters may have occurred. Between them, there is only the Karabük fault that satisfies the dipping sense of the fault plane solution. The Karabük fault is associated with the epicenter K. As previously mentioned, this epicenter was very close to one of the aftershocks. The Karabük fault may, therefore, correspond to the fracture whose activity is involved in the 1944 earthquake. Could this fault accommodate fault movements, as suggested by the focal mechanism? According to

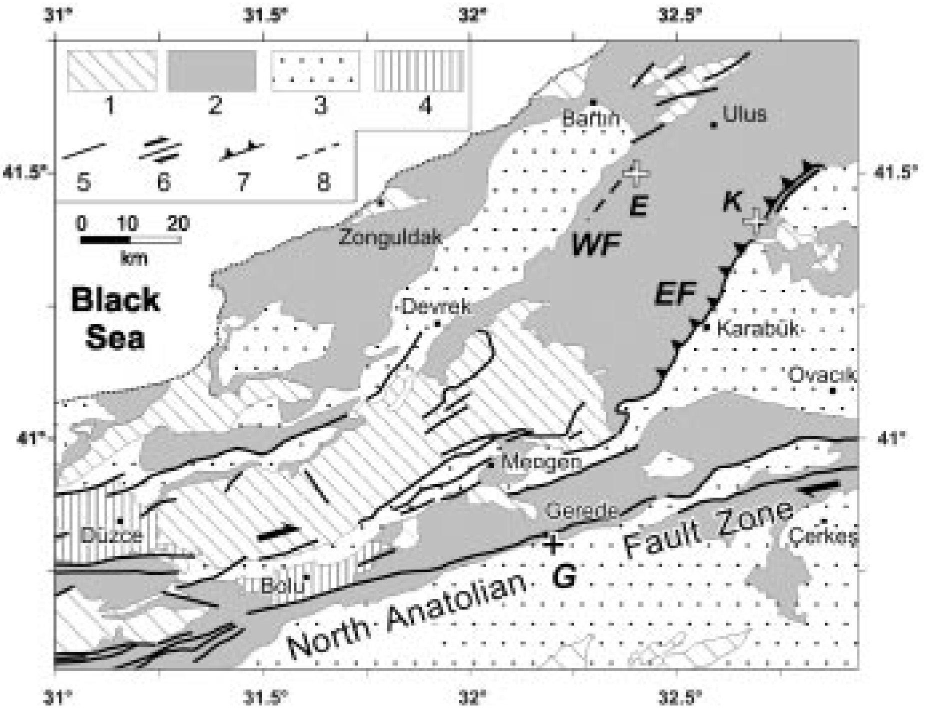

Figure 2. Simplified geological map of the area studied (Key to legend. 1: Paleozoic units; 2: Mesozoic units; 3: Tertiary units; 4: Quaternary basin deposits; 5: Fault; 6: Strike-slip fault; 7: Thrust fault; 8: Probable fault. Geological data from 1/500.000 scaled geological map (Zonguldak Sheet, MTA) and Tüysüz (1993). E, G, and K: epicenter locations for the 1944 earthquake. EF (Eastern fault) and WF (Western fault) are two fracture zones discussed in text).

Şekil 2. Çalışma alanının basitleştirilmiş jeoloji haritası (Simgeler: 1: Paleozoyik birimler; 2) Mezozoyik birimler; 3: Tersiyer birimleri; 4) Kuvaterner havza çökelleri; 5) Fay; 6) Doğrultu atımlı fay; 7) Bindirme fayı; 8) Olası fay. Jeolojik veriler: 1/500.000 ölçekli jeolojik harita (Zonguldak paftası, MTA) ve Tüysüz (1993). E, G ve K: 1944 depreminin merkezüstü yerleri. EF ve WF metinde tartışılan kırık zonları).

this mechanism, the strike-slip component is dominant along the FP1, since the rake of the movement is 16° (see Figure 2). This information suggests a fault surface along which dominantly horizontal displacements are accommodated. The topographic trace of such a fault should be linear. This point will be considered in the following section with the help of digital elevation models. In the next section, crustal deformation suggested by another regional earthquake will be considered to see if the zone near the Karabük fault may deform similar to the regime indicated by the 1944 earthquake mechanism.

SEISMIC DATA VERSUS TOPOGRAPHY

The seismic data is associated with topographic information of digital elevation models (see Figure 3). Both the K and E epicentral locations shown in Figure 3 fall near to lineaments, the lineament corresponding to the Karabük fault being much more pronounced. This lineament separates the topographically higher western Cretaceous units with a markedly rough surface from the more flat eastern Tertiary units. The trace of the lineament is almost rectilinear, suggesting the presence of a fault accommodating

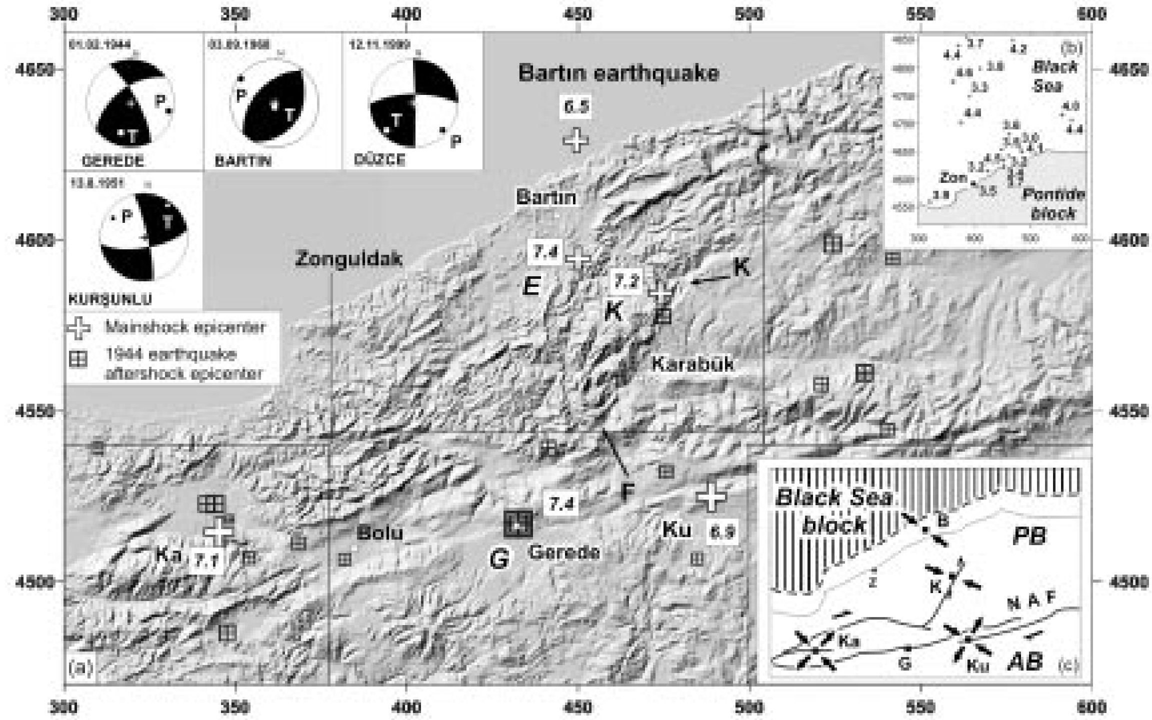

Figure 3. (a) The 1/250.000 scaled digital elevation model of the region showing the epicentres of the major earthquakes of the study area (for E, K and G, as in Figure 1. The 1944 aftershock data from Gencoğlu et al. (1990). Bartın data: Alptekin et al. (1986). Ka: Düzce data: USGS - NEIC (2003); Ku: Kurşunlu data: Eyidoğan et al. (1991). Seismic parameters are given in Tables I and II. The trace of the Karabük fault is shown by two arrows lettered K and F). (b) Epicenters of earthquakes occurring in the Black Sea near to the Pontide block (Data from USGS - NEIC (2003)). (c) Simplified seismo-tectonic map of the study area (The tectonic regime changes from strike-slip faulting between the Pontide block (PB) and Anatolian block (AB), to thrusting between the Pontide block and the Black Sea block. This is evidenced by focal mechanisms of the Düzce (KE) and Kurşunlu earthquakes (KU), associated with transcurrent faulting, and of the Bartın earthquake (BE), associated with thrusting).

Şekil 3. (a) Çalışma alanındaki önemli depremlerin merkezüstlerini gösteren 1/250.000 ölçekli sayısal arazi modeli (E, G ve K: Şekil 1'in aynısı. 1994 artçı depreminin verisi Gencoğlu vd. (1990)'dan alınmıştır. Bartın verisi: Alptekin vd. (1986). Ka: Kaynaşlı verisi: USGS - NEIC (2003); Ku: Kurşunlu verisi: Eyidoğan vd. (1991). Sismik parametreler Çizelge I ve II'de verilmiştir. Karabük fayının izi, uçlarında K ve F harfleri bulunan iki okla gösterilmiştir.) (b) Pontid bloku yakınında Kara Deniz'in depremselliği. (Veriler: USGS - NEIC (2003)). (c) Çalışma alanının basitleştirilmiş sismo-tektonik haritası. (Tektonik rejim, Pontid bloku (PB) ile Anadolu bloku (AB) arasında doğrultu atımlı faylanmadan (Kurşunlu (KU) ve Düzce (KE) depremleri), Pontid bloku ile Kara Deniz bloku arasında ters faylanmaya geçmektedir (Bartın (BE) depremi)).

dominantly horizontal displacements. This topographic signature of the Karabük fault is in agreement with previous considerations deduced from the focal solution.

THE BARTIN EARTHQUAKE AND REGIONAL TECTONICS

In 1968, an earthquake occurred offshore, in the Black Sea, near Bartın (see Figure 3), in a position more northerly than the epicenter K with respect to Gerede (Alptekin et al., 1986). The focal mechanism of the Bartın earthquake shows that the crustal area near Bartın is presently deforming under contractional forces, with a P axis orientation trending N126°. The direction of the crustal shortening in Bartın is comparable to those deduced from the NAF earthquakes (see Figure 3) (Kurşunlu earthquake: 123° and Düzce earthquake: 133°). Seismic data thus suggest a regional ESE-trending horizontal shortening direction, in average. This direction should create an important thrusting component along the c. N40°E trending Karabük fault. However, the focal mechanism of the 1944 earthquake indicates a fault movement with rather transcurrent faulting (rake 16°), and a smaller thrusting component. This point is not clear in the present scenario. Further field observations along the Karabük fault may shed light to clarify this point.

Near the North Anatolian Fault (NAF) zone, the crustal deformation is of simple shear type, accommodated mainly by strike-slip faulting, whilst at the Black Sea margin, pure shear type of deformation taken up by thrusting occurs at present. Oblique faulting can be thought to be the intermediate state between these two deformational types. Consequently, oblique faulting may occur between the Black Sea and the NAF zones, or within the Pontide block. The Karabük fault zone may be a structural example of this type of deformation the inner parts of the Pontide block may experience.

The mechanism of the Bartın earthquake suggests thrusting at the Black Sea margin, a small deep-sea basin of possibly oceanic nature (Dercourt et al., 1986; Philip et al., 1989). The crust of the Black Sea locally deforms as evidenced by seismic activity (see Figure 3b). However, stresses appear to concentrate to generate major earthquakes between the Black Sea and the Anatolian landmass in a place near the shore, probably at the transition zone between the continental and oceanic crusts (Alptekin et al., 1986). This suggests that the continental crust overthrusts the oceanic crust of the Black Sea. The origin of the crustal shortening in the NW Anatolian sliver or the Pontide block (see Figure 3c) between the NAF and the Black Sea is not very clear. Reilinger et al. (1997) ascribe this deformation to the residual strain established at the north of the NAF. In deed, the NAF assures the displacements of the Anatolian block and frictional forces exist along its surface as evidenced by earthquakes the fault generates. Stresses rising from this friction may be transmitted to the Pontide block causing seismic deformation at its boundary with the Black Sea block. This paper suggests that shortening is accommodated by oblique faulting within the Pontide block, a thesis that has to be verified by further research.

CONCLUSIONS

The study of the geological and topographical data to decipher the complex epicentral dispersion of the main shocks of the 1944 earthquake leads to the conclusion that besides the Gerede epicenter, one of the other proposed epicenters, namely the epicenter determined by the Kandilli Observatory, may have played a role during the earthquake. A possible seismic scenario is that the transpressional Karabük fault was first reactivated and this first motion was followed immediately by the release of the energy accumulated along the Gerede segment of the North Anatolian Fault (NAF) zone. The location and faulting mechanism of another major regional earthquake, the Bartın earthquake, suggest block convergence between the continental crust of the southern NW Anatolia and the possibly oceanic crust of the northern Black Sea. The Pontide block remaining between the NAF and the Black Sea block is now shortening likely due to the transmission of the NAF-linked frictional stresses towards the Black Sea-Pontide block convergence zone. The oblique-slip faulting that the Karabük fault may have accommodated can be considered as a transitional state of deformation between the pure shear deformation occurring at the Black Sea margin, at the north, and the simple shear deformation occurring along the NAF, in the south.

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