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Determining the main strand of the Eskişehir strike-slip fault zone using subsidiary structures and seismicity: a hypothesis tested by seismic reflection studies

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Abstract: The Eskişehir Fault Zone is one of the major neotectonic structures of Turkey, extending from İnegöl (Bursa) to Cihanbeyli (Konya). The fault zone presents a considerable seismic risk for the city of Eskişehir but the exact locations of active segments and the source of the major seismic event, the 1956 earthquake (M = 6.5) that occurred in the instrumental period (from 1900 to 2013), have been debated in recent literature. The structural data obtained from field studies indicate an approximately N60W-trending main strand of the right lateral strike-slip Eskişehir Fault Zone. This trend corresponds to the en echelon bends on the course of the Sarısu River. Using this concurrence, the positions of Bahçehisar and the Çukurhisar-Sultandere segments are proposed and checked by seismic reflection studies. The seismic sections disclosing positive flower structures confirm the hypothesized position of the Çukurhisar-Sultandere segment. The relocation of epicenters and focal mechanism solutions of seismic events in 1956, 1990, 2010, and 2013 indicate that the Çukurhisar-Sultandere segment might be the rupture source of the 1956 event and is a possible potential seismic source for an earthquake that could seriously affect the Eskişehir settlement.

Key words: Neotectonics, Turkey, Eskişehir, earthquake, focal mechanism solutions, seismic reflection method

1. Introduction

The North Anatolian Fault Zone and the East Anatolian Fault Zone are well-known neotectonic structures of Turkey (Figure 1). The Anatolian plate moves westward along these fault zones (McKenzie, 1972; Şengör, 1979; Şengör et al., 1985). Apart from these bordering structures, there are other internal fault zones on the Anatolian plate, such as the Eskişehir Fault Zone (Ketin, 1968; Şengör et al., 1985; Şaroğlu et al., 1987; Yaltırak, 2002; Dirik and Erol, 2003; Ocakoğlu, 2007), the Tuzgölü Fault Zone (Tromp, 1942; Toprak and Göncüoğlu, 1993; Dirik and Göncüoğlu, 1996; Çemen et al., 1999), the Central Anatolian Fault Zone (Koçyiğit and Beyhan, 1998), and the Kırıkkale-Erbaa Fault Zone (Şengör et al., 1985, 1989; Polat, 1988) (Figure 1).

Although these fault zones are considered to be secondary structures, their roles in the internal deformation of the Anatolian plate are very important for seismic hazard assessment, such as, for example the Eldivan-Elmadağ pinched crustal wedge (Seyitoğlu et al., 2000, 2009). One of these subordinate structures, the Eskişehir Fault Zone, which extends from İnegöl (Bursa) to Cihanbeyli (Konya) (Figure 1), is a relatively well-studied example; however, there is no consensus about its age or its role in the deformation of the Anatolian plate.

The Eskişehir Fault Zone was drawn on the regional geological maps of Ketin (1968), Şengör et al. (1985), and Şaroğlu et al. (1987). Later, Şaroğlu et al. (2005) presented its subdivisions as the Dodurga, Kandilli, İnönü, Osmangazi, and Kaymaz segments.

A regional significance has been attributed to the Eskişehir Fault Zone. Barka and Reilinger (1997) suggest that this fault zone, together with the Fethiye-Burdur Fault, constitutes the border between central and west Anatolian neotectonic subdivisions. Koçyiğit and Özacar (2003) also proposed the Eskişehir Fault Zone as a border of the West Anatolian extensional province. The evaluation of Yaltırak (2002) is quite different, as according to that study, the Eskişehir Fault Zone extended from Thrace to Central Anatolia and the North Anatolian Fault Zone cuts the Eskişehir Fault Zone in the Sea of Marmara.

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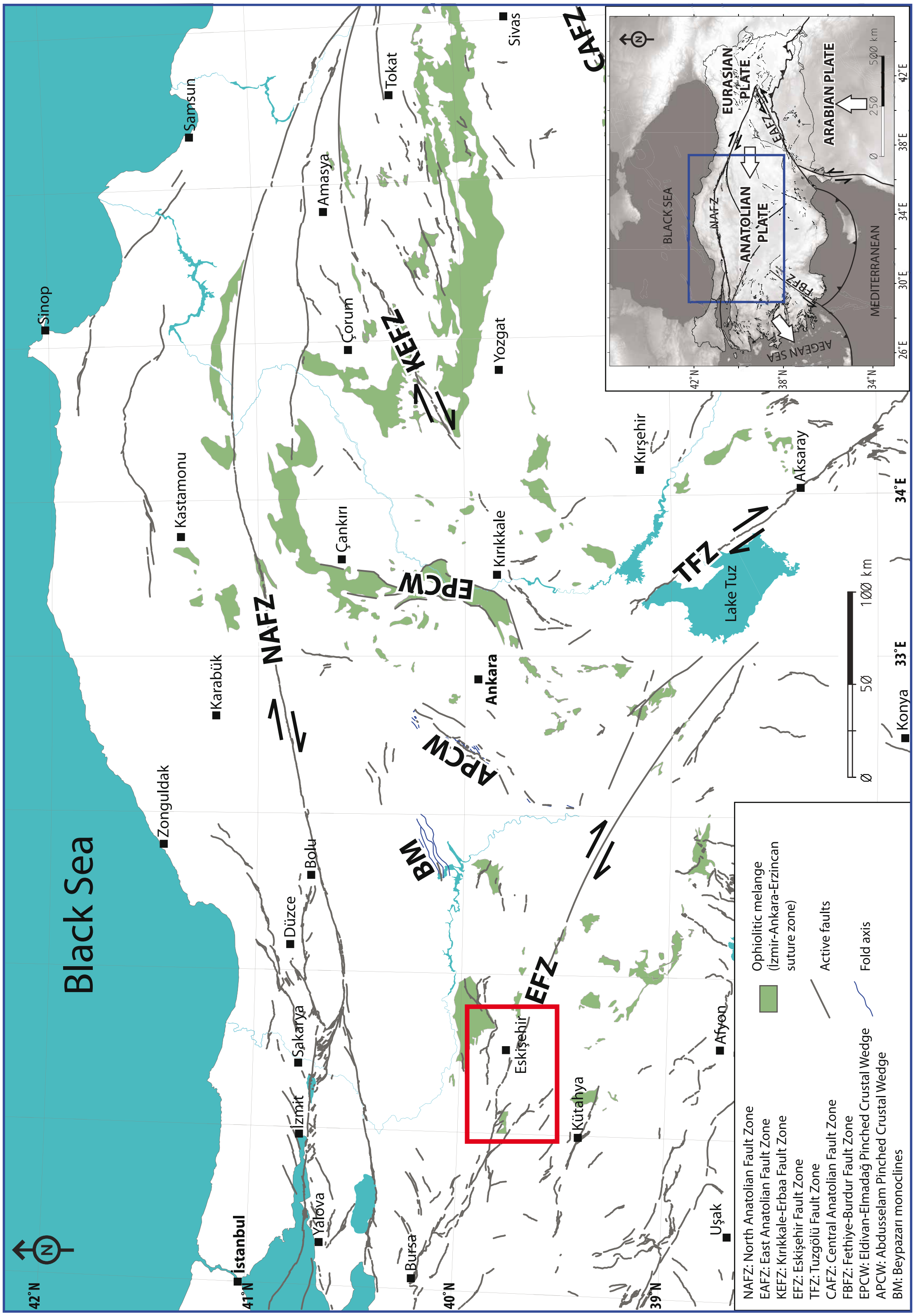

Figure 1. Eskişehir Fault Zone in the neotectonic framework of Turkey. See text for explanations.

There are 2 different views concerning the nature of the western sector of the Eskişehir Fault Zone. The first view presumes that a right lateral strike-slip fault is superimposed by younger normal faults (Gözler et al., 1985; Yaltırak, 2002; Koçyiğit, 2005; Ocakoğlu, 2007). Koçyiğit (2005) indicated that the İnönü-Eskişehir Fault Zone shows an oblique-slip normal fault character and noted that the older dextral strike-slip movements are overprinted by the younger normal faults (see also Yaltırak, 2002). Moreover, Ocakoğlu (2007) evaluated the Eskişehir Fault Zone between Bozüyük and Alpu as a post-Pliocene active normal fault zone that postdates the NW-trending strike-slip faults. The second view considers that active strike-slip faults dominate the region (Altunel and Barka, 1998; Şaroğlu et al., 2005; Ayday et al., 2001; Seyitoğlu et al., 2010; Tün et al., 2010).

In order to resolve the above discrepancies concerning the actual nature of the Eskişehir Fault Zone, the current study acquired structural data from the region, on the basis that the observed subsidiary structures can be used to determine the main strand of the strike-slip fault in the region, something that has not previously been recognized. This hypothesis was tested by seismic reflection data and the results revealed very important implications for the assessment of the earthquake risk to the Eskişehir settlement, where 682,000 people live.

2. Geomorphology of the area

The Eskişehir plain is an E-W-trending depression that is narrow in the west around the town of İnönü, widening towards the east (Figure 2). The Quaternary alluvium (i.e. the Yukarı Söğütönü location: Saraç, 2003) reaches a maximum thickness of 20 m to the west of Eskişehir and north of Turgutlar (Tün, 2013). The eastward-flowing Sarısu River follows E-W and NW-SE trends and joins the Porsuk River SW of the Eskişehir settlement. The Porsuk River flows NE and turns in an E-W direction in the city center. Another change in the course of the Porsuk River is found to the east of Eskişehir, where it turns first to the NE and then again to an E-W direction. While the Porsuk River and its tributaries subdued the topography of the southern margin of the Eskişehir plain, that of the northern margin reaches an elevation of up to 1819 m (Figure 2).

Previous geological studies dealing with the active tectonics of the area (Altunel and Barka, 1998; Ocakoğlu, 2007; Emre et al., 2011) mainly used field observations and geomorphology and showed no consensus on the trace of active faults except for the case of 2 areas, the first situated south of the town of İnönü and the other situated SE of Sultandere, where the faults create a noticeable morphology (Figure 2). Most of the faults drawn by previous studies on the southern margin of the Eskişehir plain are NW-SE- and E-W-trending. The changes in the trends are either drawn as a continuing curvature or as stepping segments. In the northern margin, however, the faults generally have NE-SW, NW-SE, and E-W trends following overall topographical differences (Figure 2).

3. Structural data on the western Eskişehir Fault Zone

Altunel and Barka (1998) determined the Eskişehir Fault Zone between İnönü and Sultandere to be a transtensional structure, using field observations and a focal mechanism solution of the 20.02.1956 (M = 6.5) Eskişehir earthquake (McKenzie, 1972). They realized that differently orientated reverse, right, and left lateral faults and normal faults are the structural elements of a right lateral shear zone, but they made no attempt to determine the main strand of the strike-slip fault from these subsidiary structures.

Our study area extends from Bozüyük to the west of Sultandere in an E-W direction, and from Eğriöz to Doğuluşah in an N-S direction (Figures 2 and 3a). On the road between Bozüyük and İnönü, overturned folds of Neogene sedimentary layers with their axis trending N50-75E (Figure 3a, locations 7 and 8; Figure 4; Figure 5, datum [1]) and small thrusts trending N80E and dipping 36NW (Figure 5, datum [2]) have been observed. Moreover, N42W-trending right lateral and N18E-trending left lateral shear fractures (Figure 5, data [3, 4]), and N80E, 45NW-thrusting surface are seen on the road from Bozüyük to İntikam Tepe, after passing the village of Saraycık (Figure 3a, locations 9 and 10) (Figure 5, datum [5]). To the west of İnönü, at the Turkish Aeronautical Association Training Center, a remarkable fault surface (N45W, 90°) with nearly horizontal right lateral slickenlines (rake: 8°) is exposed (Figure 3a, location 12; Figure 6). This fault clearly cuts the E-W-trending İnönü oblique normal fault (N75E, 80NW, rake: 44°; Figure 3a, location 13) and continues towards the SW. Therefore, it cannot be evaluated as a transfer fault of the İnönü normal fault (Figure 7). On the Kütahya–İnönü road, a basalt flow is cut by open fractures filled with calcite, trending N05E, 90° (39.79866708°N, 30.21192019°E; Figure 3a; Figure 5, datum [6]). Another open fracture trending N30W is observed south of İntikam Tepe (Figure 5, datum [7]; 39.82548643°N, 29.99430346°E). All these observed subsidiary structures must have been created by a major right lateral shear zone trending N57-60W in the region (Figure 5, datum [8]).

It is interesting to note that the Sarısu River is diverted 4.5 km right laterally to the NW of İnönü along the N60W strike. It is highly probable that this line corresponds to the Bahçehisar segment of the Eskişehir Fault Zone (Figure 3a). Further towards the east, the course of the Sarısu River is redeflected parallel to the Bahçehisar segment. It is proposed that this 18-km deflection is related to the en echelon Çukurhisar-Sultandere segment of the Eskişehir

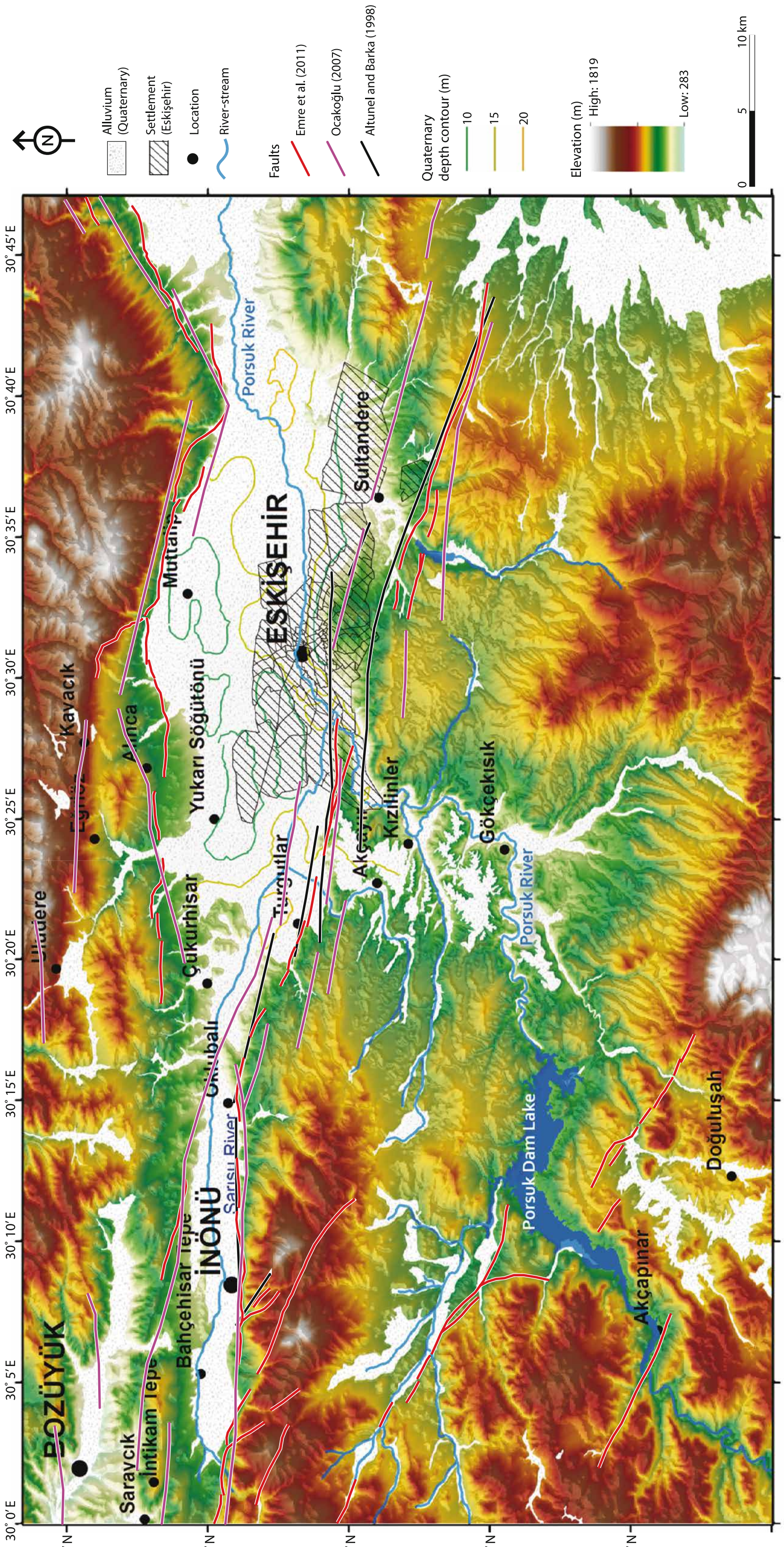

Figure 2. The geomorphology of the Eskişehir area and active fault traces from previous studies (Altunel and Barka, 1998; Ocakoğlu, 2007; Emre et al., 2011).

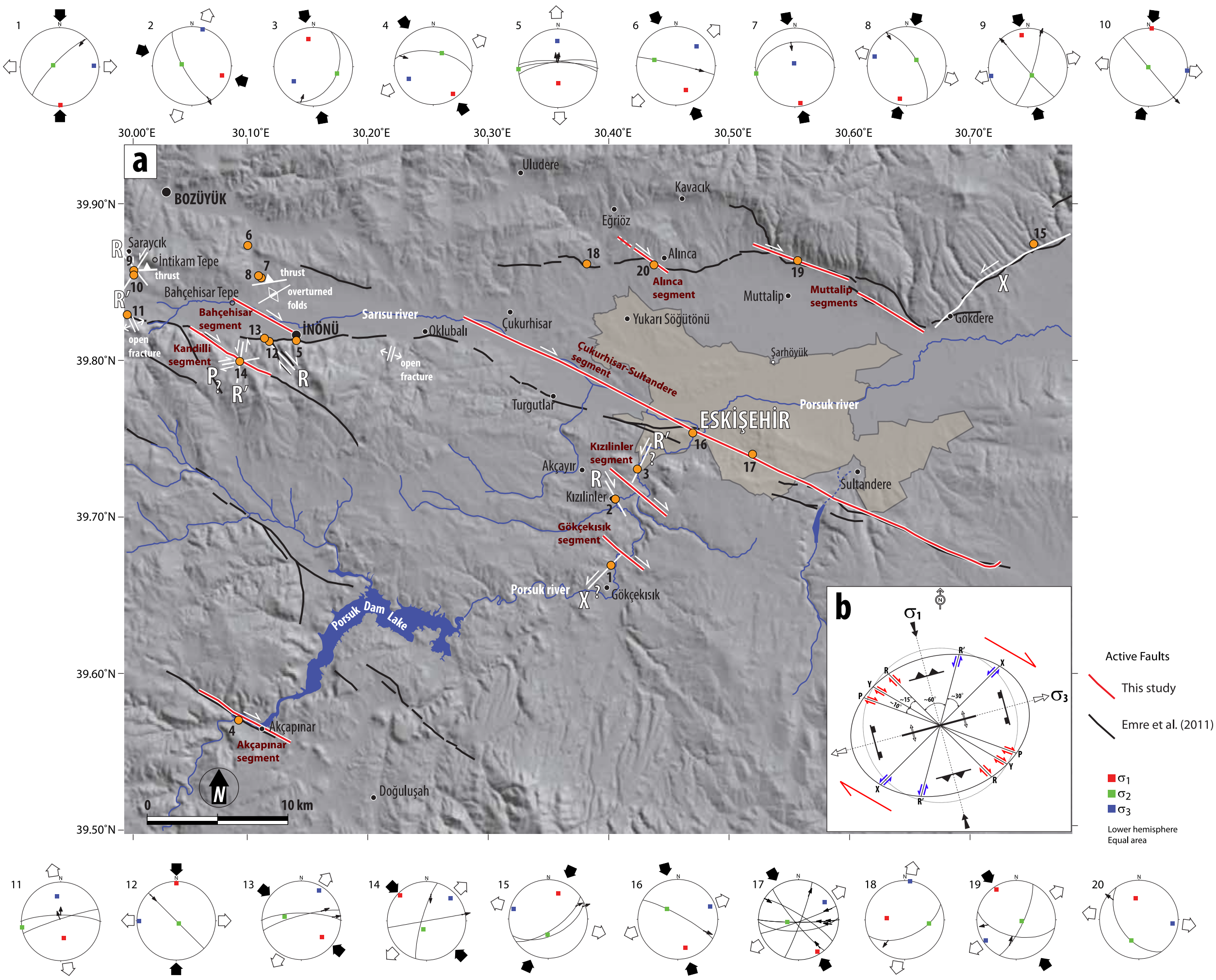

Figure 3. **(a)** Structural geology map of Eskişehir area. The observation locations are numbered on the map and the details of fault surfaces with striations are presented on the lower hemisphere equal-area projections. Red lines represent strike-slip active faults; white lines are subsidiary structures (after Seyitoğlu et al., 2010 and Tün et al., 2010). Black lines are from the MTA active fault map (Emre et al., 2011). **(b)** Theoretical position of Riedel shears and subsidiary shear fractures with related structures (i.e. normal, thrust faults, and fold axis) in a right lateral shear zone after Tchalenko (1970) and Bartlett et al. (1981). The trend N60W is given for comparison with the observed structures around Eskişehir.

Fault Zone (Figure 3a). However, it is not certain whether these deflections on the Sarısu River were created by the Bahçehisar and Çukurhisar-Sultandere segments or if the river follows the route of existing fault segments.

Using the subsidiary structures observed in the study area, the major en echelon segment of the Eskişehir Fault Zone is determined to be in the Eskişehir Valley, comprising a strike of N60W that extends from Çukurhisar to the SE of Sultandere and is approximately 40 km in length. The Çukurhisar-Sultandere segment provides fault surfaces in 2 locations (Figure 3a, locations 16 and 17; Figure 8), bearing right lateral strike-slip structural data. The SE continuation of this segment creates a shear zone on the Neogene limestones and its topographical difference can be clearly observed in the field. The segment ends with a NE-trending curvature (Figure 3a). The geophysical data taken from this segment are presented in the next section.

Around the town of İnönü, the E-W-trending normal faults are cut by the Riedel shear of N45W-trending right lateral strike-slip faults, for example at the location of the Turkish Aeronautical Association Training Center as shown in Figure 3a, locations 12 and 13. These normal faults are not compatible with the principal stress configuration of the Eskişehir Fault Zone (Figure 3a, locations 5 and 13; Figure 3b). Therefore, the E-W-trending normal faults must belong to the earlier extensional tectonics in western Turkey. The strike-slip tectonics is younger than the NNE extension and is the current tectonic regime in the region.

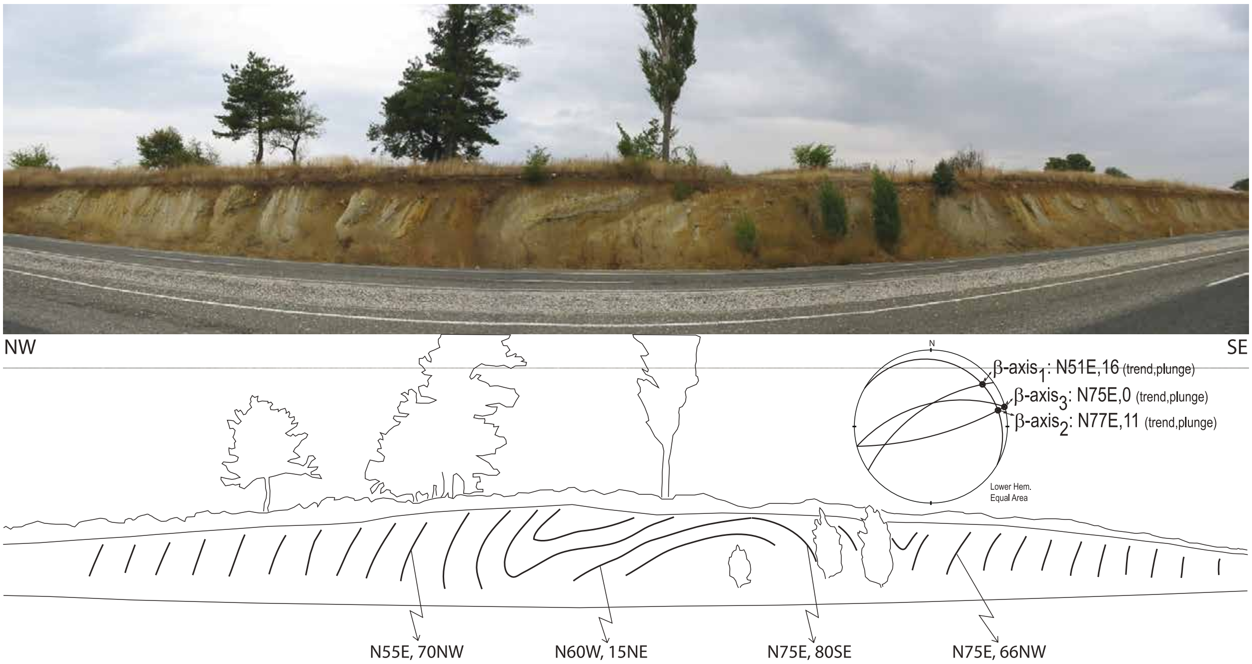

Figure 4. Photograph and its sketch of the overturned folds with beta diagram along the road cut between Bozüyük and İnönü. For position, see Figure 3a, locations 7 and 8.

The other en echelon segments of the Eskişehir Fault Zone also deflect the course of the Porsuk River between Eskişehir and Kütahya. Around the village of Kızılinler and in the northern part of Gökçekısık village, Riedel: R (N30W, 73SW) and anti-Riedel: R′ (N26E, 38SE) shear fractures and a possible X fracture (N44E, 78NW) indicate a major fault trending approximately N50W, which corresponds to the 1.5-km and 1-km right lateral deviations of the Porsuk River, called the Kızılinler and Gökçekısık segments, respectively (Figure 3a, locations 1, 2, and 3).

At the southern end of the Porsuk Dam Lake, the Akçapınar segment, which possesses a fault surface of N80W, 60NE, corresponds to a 2.5-km right lateral diversion of the Porsuk River (Figure 3a, location 4). In the northern Eskişehir Valley, the right lateral strike-slip faults with normal components constitute the Alınca and Muttalip segments that run nearly parallel to the Çukurhisar-Sultandere segment (Figure 3a, locations 19 and 20).

All these observations indicate that the Eskişehir Fault Zone is a wide shear zone with a strike at nearly N60W and a width of 60 km, lying between the cities of Eskişehir and Kütahya. Comparing the structural data presented in Figure 3a and Table 1 with the theoretical right lateral shear zone (Figure 3b) shows us that the Y shear corresponds to the Bahçehisar, Çukurhisar-Sultandere, Kızılinler, Gökçekısık, Akçapınar, Alınca, and Muttalip segments (Figures 3a and 3b). The Çukurhisar-Sultandere segment has been evaluated as the main strand of the Eskişehir Fault Zone in terms of its length.

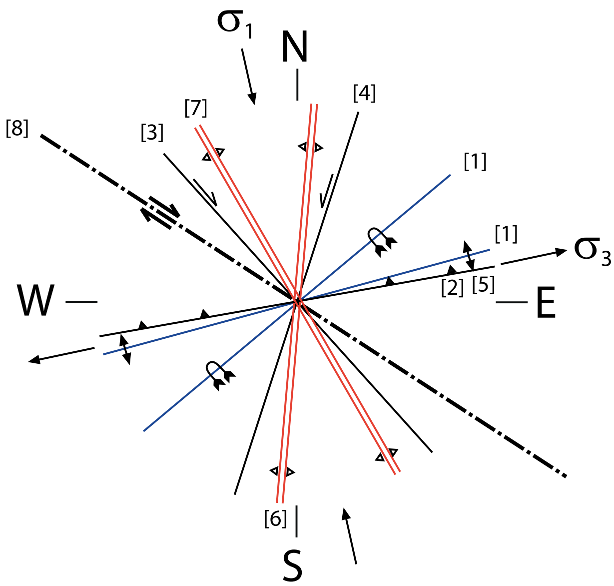

Figure 5. The positions of observed subsidiary structures [1 to 7], and the determination of the main strike-slip strands of the Eskişehir Fault Zone, namely Bahçehisar and Çukurhisar-Sultandere segments [8]. See text for further explanation.

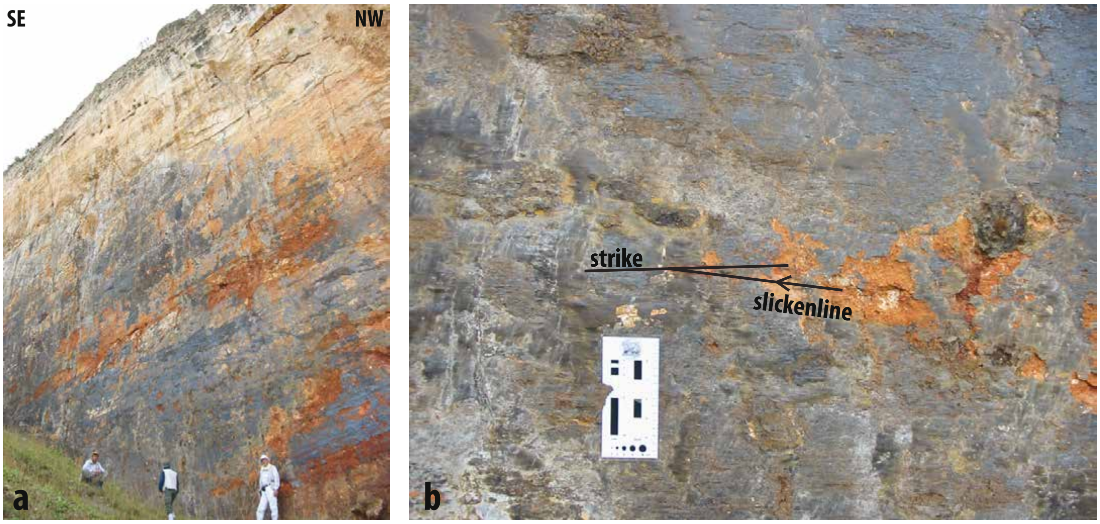

Figure 6. Photos of a Riedel shear (N45W, 90°, rake: 8°) of the major Eskişehir Fault Zone near the Turkish Aeronautical Association Training Center. This structure cuts the nearly E-W-trending normal fault. For position, see Figures 3a and 7, location 12.

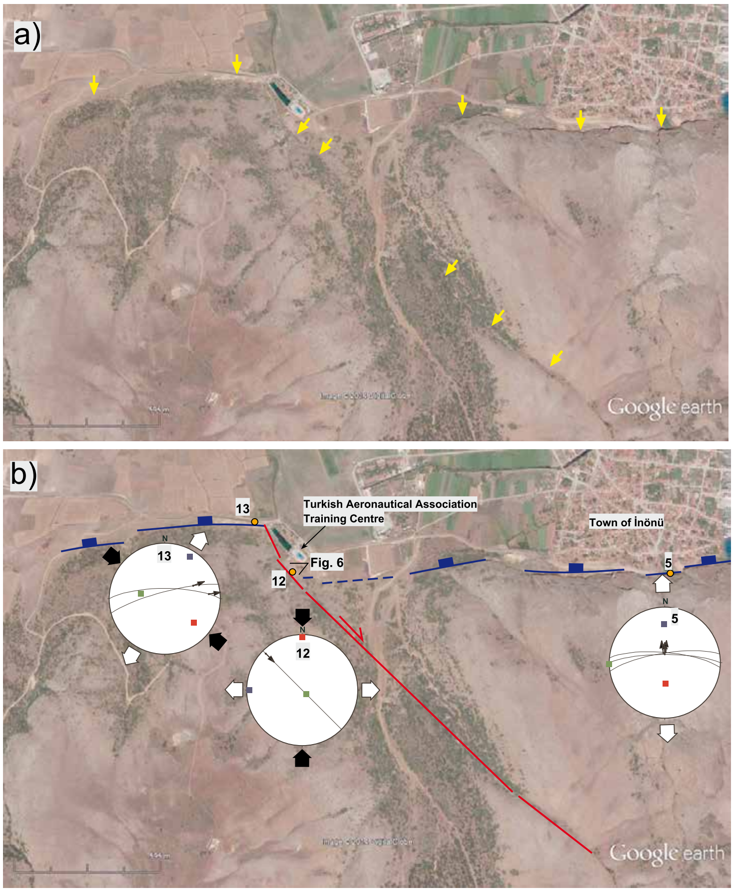

Figure 7. The cross-cutting relationship between NW-SE-trending strike-slip and E-W-trending normal faulting in the west of İnönü town. **(a)** Uninterpreted Google Earth image. Yellow arrows show fault traces. **(b)** Normal fault traces (blue) and strike-slip fault traces (red) with the structural data. For the overall positions of locations 5, 12, and 13, see Figure 3a.

Figure 8. The shear zone of Çukurhisar-Sultandere segment. The hammer (30 cm) is located on the polished fault surface. For position, see Figure 3a, location 17.

4. Seismic reflection studies on the Çukurhisar-Sultandere segment

Several seismic reflection surveys with P-Gun and hammer sources have been performed on the Çukurhisar-Sultandere segment. This segment is partly covered by recent alluvium (Figure 9), and its location is predicted by the subsidiary structures (see above).

4.1. Seismic data acquisition and processing

Field layout: off-end for P-Gun surveys; symmetrical split-spread for hammer surveys. Sampling interval: 0.5 ms for P-Gun surveys; 1 ms for hammer surveys. Recording time: 4 s for P-Gun surveys; 2 ms for hammer surveys.

Processing sequences: (1) static correction, (2) first band-pass filtering (trapezoid: 1–5–90–100 Hz), (3) automated gain control (1/4 of the recoding time), (4) first-breaks and ground-rolls mute, (5) common depth-point sort, (6) velocity analysis (time/velocity pairs: 80 ms - 800m/s, 100 ms - 1500 m/s, 150 ms - 2200 m/s), (7) stacking, (8) second band-pass filtering, (9) horizontal smoothing (Weights: 0.5, 1.0, 1.0, 1.0, 0.5), (10) time trimming, (11) time-to-depth conversion, (12) predictive deconvolution.

4.2. Interpretation of the seismic sections

The 4 P-Gun surveys (G-7, G-2, G-8, G-9) were performed on the Çukurhisar-Sultandere segment from the NW to SE (Figure 9, Figures 10a–10d). In these seismic sections, the overall position of the shear zone was recognized easily due to the discontinuity of seismic layers reaching to a depth of nearly 1000 m. The southeastern sector of the Çukurhisar-Sultandere segment has an obvious morphological expression in which P-Gun survey (G-10) indicated clearly its transpressional nature (Figure 11). The SE end of Çukurhisar-Sultandere segment is bent towards the NE. The seismic section G-9 is located on this bend and shows reverse faulting (Figure 10d), which is further evidence for the right lateral movement on the segment.

The 7 hammer surveys provided more detailed seismic sections that penetrated to a depth of 100 m to 250 m. The seismic sections show perfect positive flower structures that reach the surface (Figures 12a–12g). A symmetrical anticline of the seismic layer at the depth of 50 m in the northern part of section B-3 is apparent and particularly noteworthy (Figure 12b). The north vergence of the asymmetric anticlines in the seismic layers between the depths of 50 and 100 m at the northern part of sections B-4 and B-6 is evident (Figures 12c and 12d). In section B-7, 3 fault branches are recognized, being northern, middle, and southern branches. The northern branch of the fault creates an apparent deformation on the seismic layers at a depth of 50 m. This deformation is not obvious in the seismic layer at 100 m of depth, but the deformation on the seismic layer around the depth of 200 m allows us to draw the northern branch of the fault from 50 to 200 m (Figure 12e). The middle branch of the fault in section B-7 reaches the surface. Especially in the top 50 m, the fault could be drawn confidently by using distinctive displacements of the seismic layers (Figure 12e). The southern branch of the fault is distinguished by an intense deformation on the seismic layer at a depth of 100 m and its multiple branches can be followed upwards to the depth of 25 m (Figure 12e). The faults drawn on the NE part of section B-9 (Figure 12f) mimic the faults on the northern part of section B-7. The distinct deformation is in the lower middle part of section B-9. The SW vergence of the anticline at a seismic layer between 100 and 75 m in depth, in the middle right-hand side of section B-9, allows a major fault branch in this location to be drawn (Figure 12f). Section B-10 is an example of how horizontal seismic layers in the top 60 m are intensively deformed by the branches of the Çukurhisar-Sultandere segment under the Eskişehir plain. Due to intense deformation on the seismic layers, fault branches are drawn confidently at the northern and southern end of this section (Figure 12g). The overall conclusion from the interpretation of 7 hammer surveys is that the Çukurhisar-Sultandere segment has a transpressive nature (Figures 12a–12g).

5. Seismicity of the area

Around Eskişehir, the most significant seismic event in the instrumental period was the 20.02.1956 (M: 6.5) Eskişehir earthquake (Öcal, 1959; Canıtez and Üçer, 1967; McKenzie, 1972; Kiratzi, 2002) (Figure 13). Unfortunately, no immediate field study was performed to determine the fault responsible for this earthquake, and the isoseismal map of the event prepared based on questionnaires completed by science teachers was not adequate (Öcal, 1959). The epicenter of the main shock has been debated in the literature.

Table 1. List of the structural data obtained from Eskişehir area. For locations and lower hemisphere equal-area projections, see Figure 3a.

No.	Coordinates (geographic)		Strike	Dip	Rake	Sense of slip	σ_1		σ_2		σ_3	
	°E	°N					Trend	Plunge	Trend	Plunge	Trend	Plunge
1	30.402164	39.669112	N44E	78NW	7N	Reverse	179	4	283	76	88	13
2	30.405558	39.711393	N30W	73SW	13S	Normal	108	21	278	69	16	3
3	30.424091	39.730543	N26E	38SE	8S	Reverse	350	30	106	38	233	38
4	30.093083	39.570313	N80W	60NE	13N	Reverse	145	13	35	58	242	29
5	30.141070	39.812724	E-W	78N	90	Normal	179	59	269	0	359	31
			N81E	76NW	90	Normal						
			N85W	75NE	90	Normal						
6	30.100708	39.873372	N77W	87NE	47S	Normal	158	34	286	43	46	29
7	30.112004	39.852683	N81E	36NW	90	Reverse	171	9	261	0	351	81
8	30.109727	39.854032	N31W	66NE	0	Right Lateral	191	17	59	66	287	17
9	30.006285	39.857459	N18E	79SE	15N	Normal	349	18	154	72	258	5
			N42W	86SW	20N	Normal						
10	30.006230	39.854422	N40W	90	0	Right Lateral	5	0	90	90	95	0
11	29.994309	39.825487	N72E	85NW	90	Normal	169	54	261	1	352	36
			E-W	77N	90	Normal						
12	30.118567	39.812023	N45W	90	8N	Reverse	0	6	135	82	270	6
13	30.114554	39.814130	E-W	75N	22E	Normal	129	33	282	54	31	13
			N75E	80NW	44N	Normal						
14	30.094129	39.799342	N80E	90	9N	Normal	314	7	202	71	47	17
			N16E	80NW	33N	Reverse						
15	30.754791	39.873429	N65E	55SE	9N	Normal	22	31	182	57	286	9
			N55E	67SE	25N	Normal						
16	30.466386	39.754374	N61W	81NE	30S	Normal	165	27	314	59	68	14
17	30.518927	39.743069	E-W	85S	40E	Reverse	149	8	259	67	56	21
			N58W	80NE	0	Right Lateral						
			N20E	85SE	30S	Normal						
			N70E	86SE	20N	Reverse						
			N87E	67SE	26N	Reverse						
			N40W	82SW	19S	Reverse						
			E-W	85S	18E	Reverse						
18	30.378889	39.862512	N66E	55SE	42S	Normal	276	53	99	38	8	1
19	30.558884	39.861560	N78W	55SW	35N	Normal	327	8	103	79	236	8
			N25E	75SE	35S	Reverse						
20	30.434294	39.863860	N35W	48SW	25N	Normal	352	44	200	42	97	15

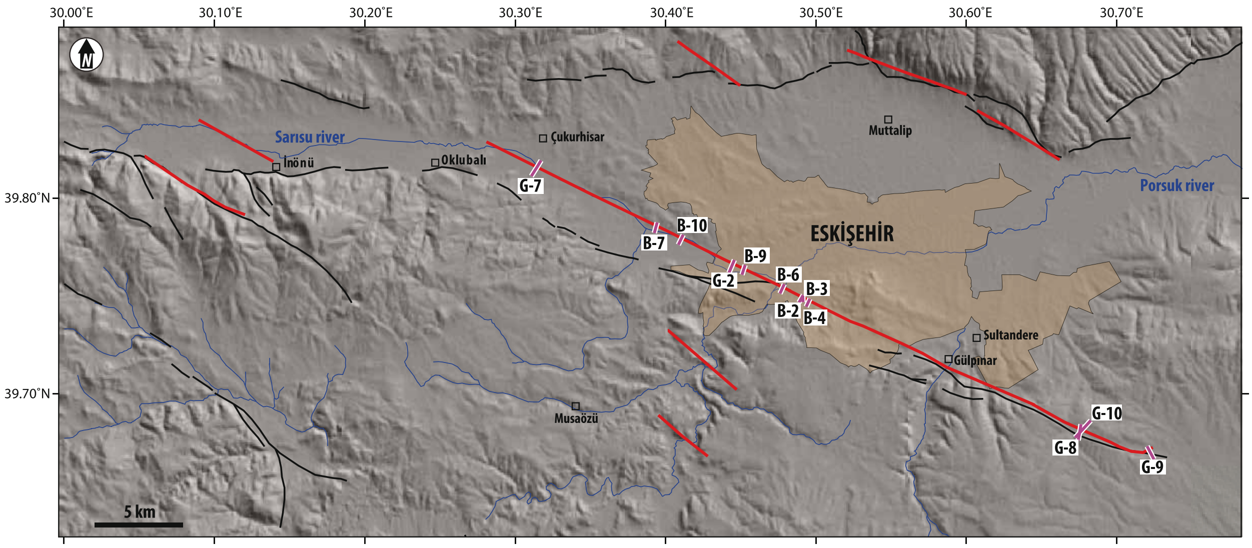

Figure 9. The locations of the P-Gun and hammer surveys on the Çukurhisar-Sultandere segment (red lines: from Seyitoğlu et al., 2010; Tün et al., 2010; present study). The faults (black lines) from Emre et al. (2011) are given for comparison.

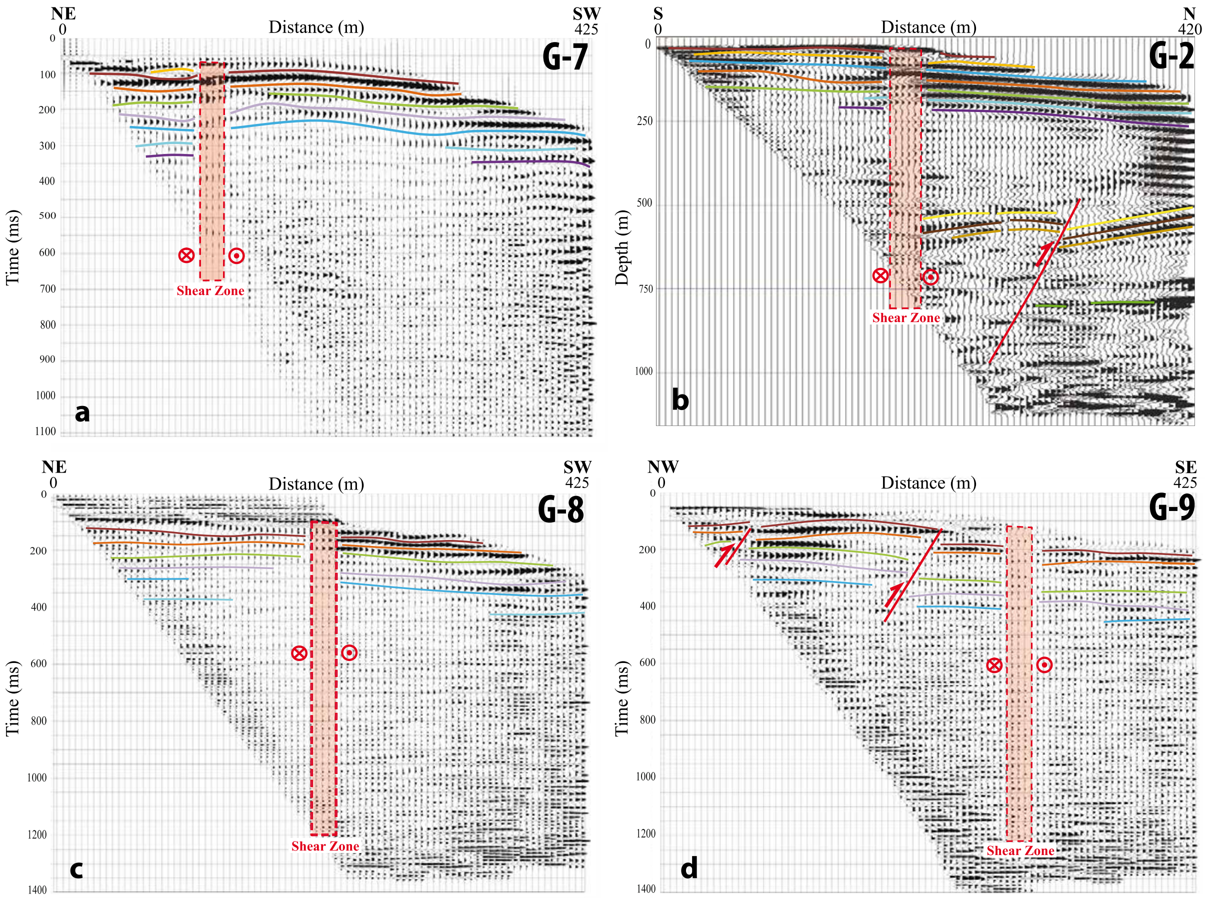

Figure 10. The seismic sections obtained from the P-Gun surveys on the Çukurhisar-Sultandere segment. For location, see Figure 9. Almost horizontal colored lines denote the seismic marker horizons. Although they are not associated with any geological layer in the present work, they are very useful in imaging the faults. Uninterpreted seismic sections are available at https://dosyam.ankara.edu.tr/bl06.

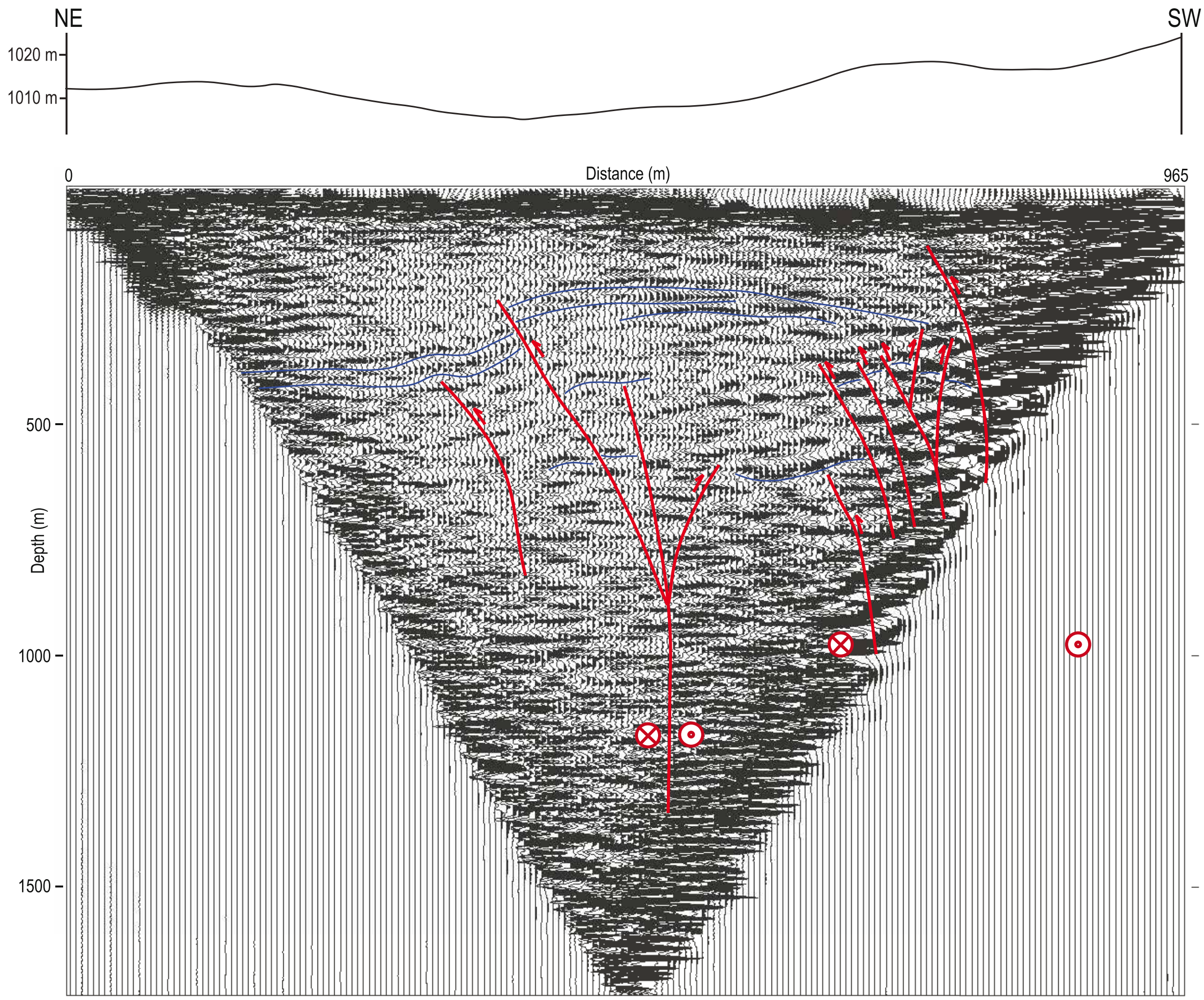

Figure 11. Seismic section G-10 obtained by P-Gun survey on the Çukurhisar-Sultandere segment. For location, see Figure 9. Topographical cross-section especially presented because, due to the dipping direction of the slope, some researchers suggest either normal faulting (Ocakoğlu, 2007) or normal component of a strike-slip fault (Emre et al., 2011) in this area, but in the seismic section the transpressional nature of the segment is obvious. Uninterpreted seismic sections are available at https://dosyam.ankara.edu.tr/bl06.

Öcal (1959) reported 2 epicenter locations from macro- and microseismic studies (Figure 13). Canıtez and Üçer (1967) and McKenzie (1972) provided focal mechanism solutions to the earthquake with epicenter locations to the north of Eskişehir (Figure 13). Altunel and Barka (1998) combined the epicenter location of Öcal (1959) with the focal mechanism solution of McKenzie (1972) and suggested that the Oklubalı-Turgutlar segment was responsible for the earthquake, unlike Şaroğlu et al. (2005), who suggested the E-W-trending İnönü segment. On the other hand, Ocakoğlu et al. (2007) and Ocakoğlu and Açıkalın (2010) pointed out that the faults located to the north of Eskişehir (the Uludere-Kavacık or alternatively the Muttalip segments) are the rupture source of the 1956 earthquake (Figure 13). As admitted by Ocakoğlu and Açıkalın (2010), there is an inconsistency between the stress directions of the Uludere-Kavacık segments (σ_3 = N48W) and that of McKenzie's focal mechanism solution (1972) (σ_3 = N24E) (Table 1 in Ocakoğlu and Açıkalın, 2010). The Muttalip segment, the second alternative proposed by Ocakoğlu and Açıkalın (2010), is also an unlikely source of the 1956 earthquake, because our structural data (Figure 3a, location 19) demonstrate a SW-dipping right lateral strike-slip fault with a normal component for the Muttalip segment, whereas the focal mechanism solution of McKenzie (1972) indicates a SW-dipping normal fault with a left lateral strike-slip component (Figure 13). Due to inconsistencies between

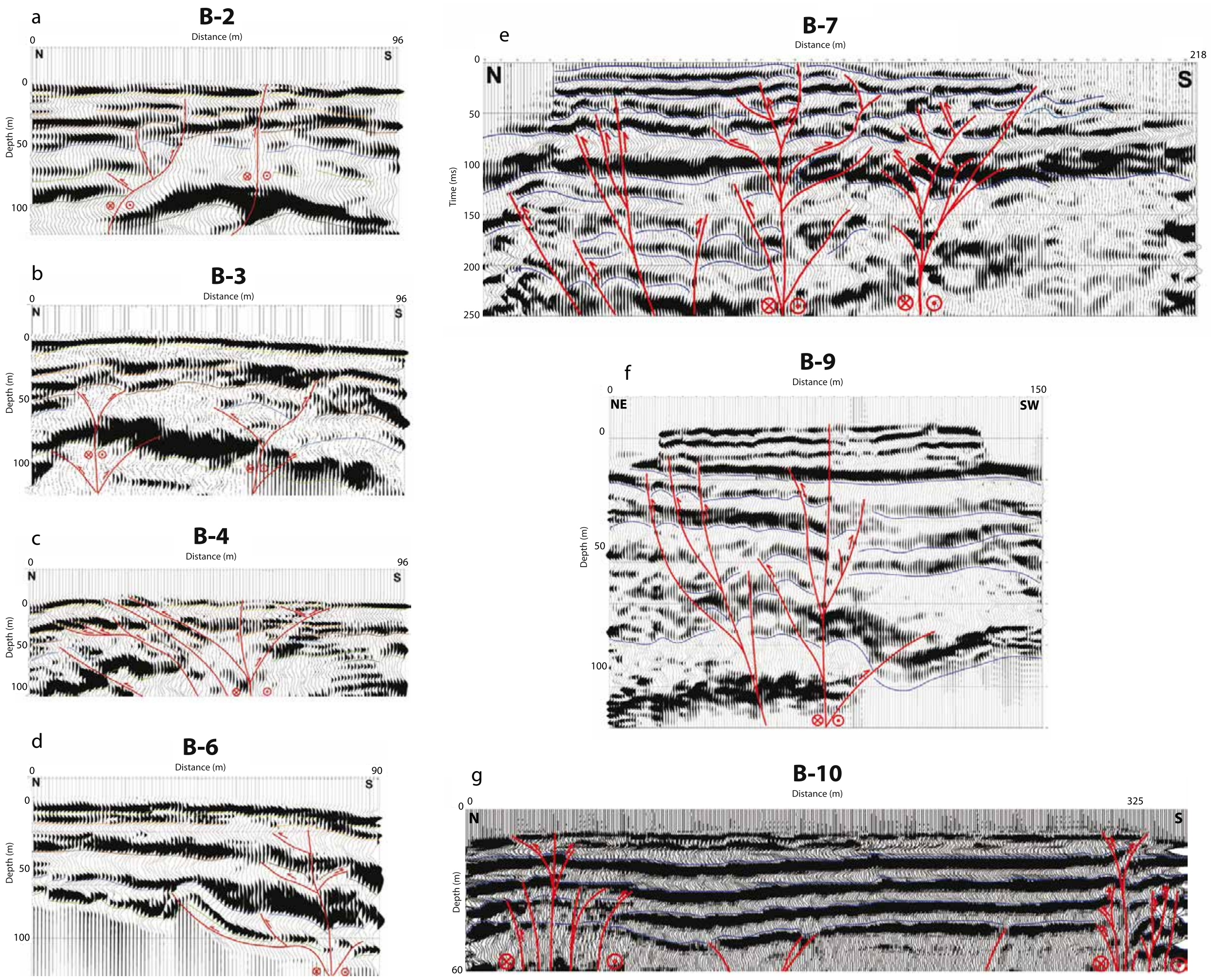

Figure 12. The seismic sections obtained from hammer surveys on the Çukurhisar-Sultandere segment. See Figure 9 for locations. Uninterpreted seismic sections are available at https://dosyam.ankara.edu.tr/bl06.

observed structures and McKenzie's focal mechanism solution (1972), the earlier epicenter location of the 1956 earthquake has been questioned and recalculated.

5.1. Relocation of the 20.02.1956 (M = 6.5) Eskişehir earthquake

The phases of the 20.02.1956 Eskişehir earthquake were obtained from bulletins of the International Seismological Summary (ISS) (Villaseñor et al., 1997). For the relocation of the 1956 Eskişehir earthquake, we used earthquake location software that is a modified version of HYPOCENTER (Lienert et al., 1986; Lienert, 1991; Lienert and Havskov, 1995). This software is capable of locating local, regional, and teleseismic earthquakes. Global travel times were calculated using the International Association of Seismology and Physics of the Earth's Interior IASP91 reference velocity model (Kennett and Engdahl, 1991).

On the basis of the ISS Bulletin, the 20.02.1956 earthquake was recorded by 145 worldwide seismological stations (Figure 14a). Before starting the relocation process, we had a total of 145 P- and 113 S-phase readings. To be able to calculate more precise coordinates and origin time, we selected the phase readings that had lower differences between observed and calculated travel times (O-C times) as given in the ISS Bulletin (http://storing.ingv.it/ISS/). With this elimination method, the numbers of stations and phase readings used in the relocation calculation were reduced to 29 stations (Figure 14b) and 29 P-phase readings, respectively. Finally, using these selected phase data, we calculated a new epicentral location (Figure 13) and origin time for the earthquake (Table 2). The origin time error and the unweighted root mean square were then obtained as 0.57 s and 0.20 s, which were reduced from their initial values of 119.58 s and 42.97 s, respectively.

The fault plane solution of the 20.02.1956 earthquake has not been computed, because we could not access the previous analogue seismograms of this earthquake.

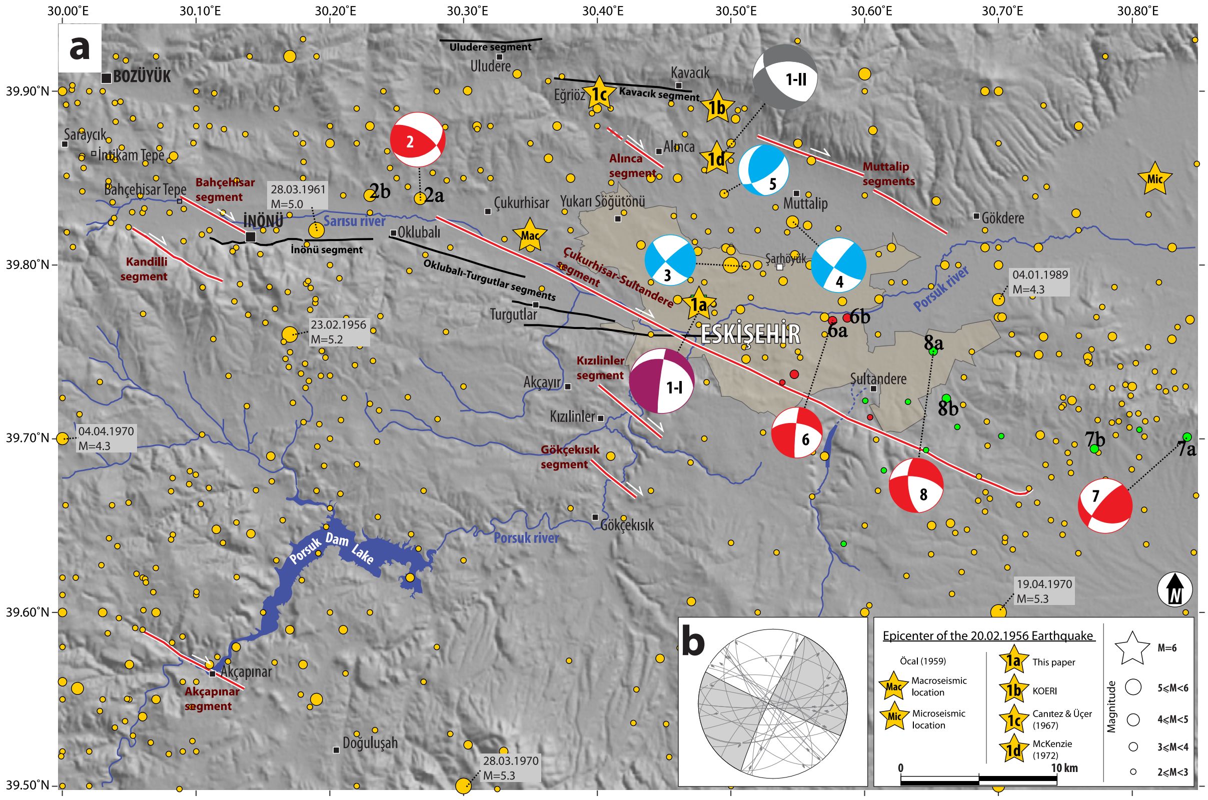

Figure 13. (a) The seismicity map of the Eskişehir area. Data from the earthquake catalog (1900–2013) of Boğaziçi University, Kandilli Observatory and Earthquake Research Institute (KOERI). Focal mechanism solutions (1-I) 20.02.1956, Canıtez and Üçer (1967); (1-II) 20.02.1956, McKenzie (1972); (2) 24.10.1990, this paper; (3) 02.10.2003, (4) 03.10.2003, (5) 04.10.2003, Ocakoğlu et al. (2005); (6) 07.02.2010, (7) 17.02.2013, (8) 01.03.2013, this paper. Aftershock distributions of 2010 and 2013 events are shown with red and green dots, respectively. See Table 2 for details of the earthquakes. The black fault segments are from Altunel and Barka (1998) and Ocakoğlu (2007). **(b)** The overall evaluation of structural data, except for locations 5, 11, and 13, is given for comparison with the focal mechanism solution of Canıtez and Üçer (1967). FaultKin software was used for kinematic analysis of fault-slip data (Marrett and Allmendinger, 1990; Allmendinger et al., 2012).

Although the ISS Bulletin contains information about the phase polarities, these are inadequate for computing the fault plane solution. Therefore, we considered the second solution proposed by Canıtez and Üçer (1967) as a focal mechanism solution for the 20.02.1956 earthquake. This choice is supported by the overall structural data presented in Figure 13b. Canıtez and Üçer's (1967) solution has an unusually low dip angle for a strike-slip fault in the region, however, and it can therefore be speculated that this solution might have a similar dip angle as the fault plane obtained from overall structural data (Figure 13).

5.2. The distribution of buildings damaged during the 1956 Eskişehir earthquake

The distribution of the damage pattern of buildings during the 1956 Eskişehir earthquake was presented by Ocakoğlu et al. (2007). Using their database, and mainly based on Öcal (1959), a reproduced map is given in Figure 15. The incidence of damaged buildings is high in 2 locations: the Kavacık-Kozkayı and Aşağı Söğütönü-Çukurhisar villages located to the north and northwest of Eskişehir, respectively (Figure 15a). If the conditions of buildings in 1956 are considered, it can be concluded that the houses in the villages could have been more poorly constructed in comparison to buildings in the city center. Therefore, a map of the rate of damaged buildings may not represent the real damage distribution, and may also contain damage due to the poor construction practices in the villages. Consequently, a map showing the number of heavily and moderately damaged buildings is more appropriate to assess the demolition effects of the earthquake (Figure 15b). However, this map should be used with caution since it may reflect the amplification of ground shaking to a certain degree. Nevertheless, the map of heavily and moderately damaged buildings (Figure 15b) together with the relocation of the epicenter of the 20.02.1956 (M = 6.5) Eskişehir earthquake and the seismic reflection data might

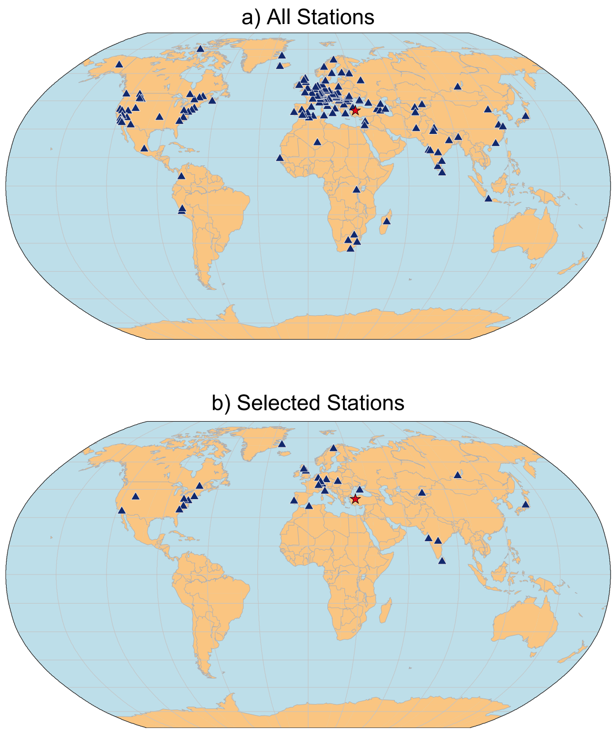

Figure 14. **(a)** The 145 worldwide seismological stations that recorded the 20.02.1956 Eskişehir earthquake. **(b)** Remaining stations after the selection procedure was applied for more reliable coordinates of the event. Epicenter of the event is shown by a star.

assist in suggesting that the Çukurhisar-Sultandere fault segment was responsible for the 1956 Eskişehir earthquake.

5.3. New focal mechanism solutions of 1990, 2010, and 2013 earthquakes

Recent seismic activities (24.10.1990, M = 4.4; 07.02.2010, M = 3.7; 17.02.2013, Md = 3.1; 01.03.2013, Md = 3.4) near the Çukurhisar-Sultandere segment have been examined in detail. Only the phase reading data of the 24.10.1990 earthquake were obtained from bulletins of the International Seismological Center (ISC; http://www.isc.ac.uk); data for the other events were retrieved from the Boğaziçi University Kandilli Observatory and Earthquake Research Institute (KOERI). We started the processes by relocating those earthquakes that had occurred recently. The previous and new locations of the events are shown in Figure 13 and Table 2.

To compute the focal mechanism solutions of the events, we used the FPFIT program (Reasenberg and Oppenheimer, 1985) that computes double-couple fault plane solutions from P-wave first motion data using a grid search method. Based on the computed results, the source of the 24.10.1990 earthquake is a NW-SE-trending right lateral strike-slip fault with a reverse component, and this concurs with the positive flower structures observed in the seismic sections given in this paper for the Çukurhisar-Sultandere segment (Figure 13). A recent earthquake that occurred on 07.02.2010 is related to a nearly E-W-trending right lateral strike-slip fault and its aftershocks (07.02.2010–14.02.2010) are located on and very close to the Çukurhisar-Sultandere segment (Figure 13). The 2 most recent earthquakes with magnitudes of larger than 3.0 occurred sequentially on 17.02.2013 and 01.03.2013. The locations of those 2013 earthquakes, including their aftershocks, are close to the southeastern tip of the Çukurhisar-Sultandere segment and the seismic activity of the area has significantly increased following 2010.

Our study also contains the locations and focal mechanism solutions of earthquakes that occurred in 2003 (Ocakoğlu et al., 2005) (Table 2; Figure 13). No processes were performed on them. All available focal mechanism solutions of the earthquakes of 1990, 2010, and 2013 that are referred to in this paper, together with the 2003 events (Ocakoğlu et al., 2005; Table 2), indicate unequivocally that the current tectonic regime is strike-slip in nature (Table 2; Figure 13). The evaluation of all focal mechanism solutions (Figure 16a) and the focal mechanism solutions plus structural data obtained from the Çukurhisar-Sultandere segment (locations 16 and 17, Figure 3a) indicate a transpressive character (Figure 16b), supporting the seismic reflection data presented in Section 4.

6. Discussion

Previous geological studies naturally used prominent topographical differences to determine active faults around Eskişehir (Figure 2). This approach has both positive and negative effects. On the positive side, it creates a common agreement among researchers about the location of an active fault, as in the case of the positions SE of Sultandere and south of the town of İnönü. It can be seen from Figure 2 that several researchers more or less agreed on the position of faults in these locations. The negative side of the morphology-dependent approach is the possible misguiding of researchers if the previous tectonic regime created prominent topographical features. Such a situation can be seen in the case of both the İnönü segment and the northwestern continuation of the Sultandere segment on the maps of Altunel and Barka (1998), Ocakoğlu (2007), and Emre et al. (2011). In these maps, E-W-trending faults are either shown as independent active fault segments or as a continuation of NW-SE-trending strike-slip fault segments (Figure 2). For example, the NW-SE-trending Sultandere segment turns toward an E-W direction SW of the Eskişehir settlement (Figure 2). This paper, however, presents a cutting relationship to the west of İnönü showing that the strike-slip faulting is younger than the E-W-trending normal faults (Figure 7). This observation leads

Table 2. Earthquake parameters and focal mechanism solutions of the seismic events around Eskişehir.

#	Date (d.m.y)	Earthquake parameters						Fault plane parameters			
			Time (GMT)	Latitude (N°)	Longitude (E°)	Depth (km)	Magnitude		Strike 1 Strike 2	Dip 1 Dip 2	Rake 1 Rake 2
1	20.02.1956	a	20:31:40.93	39.778	30.476	18.3	-	I	284 187	34 85	−172 −56
		b	20:31:37.00	39.890	30.490	40	6.4	II	140 264	56 50	−51 −133
		c	20:31:39.00	39.900	30.400	-	6.5				
		d	20:31:38.10	39.860	30.490	9	6.0				
		Mac.	20:31:35.00	39.817	30.350	23	6.4				
		Mic.	20:31:35.00	39.850	30.817	23	6.4				
2	24.10.1990	a	11:16:43.41	39.838	30.268	0.5	-	III	65	40	40
		b	11:16:44.32	39.840	30.230	18.2	4.4		302	66	123
3	02.10.2003	b	17:22:05.00	39.799	30.511	16.1	3.9	IV	135 226	76 82	172 14
4	02.10.2003	b	22:27:47.00	39.825	30.546	17.4	4.2	IV	123 214	76 82	172 14
5	04.10.2003	b	17:53:06.00	39.841	30.495	8.6	3.7	IV	56 178	67 38	122 38
6	07.02.2010	a	17:21:33.20	39.768	30.576	4.1	3.6	III	278	60	−174
		b	17:21:32.15	39.770	30.587	5.0	3.7		185	85	−30
7	17.02.2013	a	08:34:28.83	39.701	30.841	10.4	3.1	III	220	75	50
		b	08:34:28.00	39.694	30.772	7.6	2.3		113	42	158
8	01.03.2013	a	14:37:16.18	39.751	30.651	0.1	3.4	III	175	65	−30
		b	14:37:16.00	39.723	30.661	1.5	3.5		279	63	−152

a: New hypocentral parameters computed in this study.
b: Original hypocentral parameters provided by KOERI.
c: Original hypocentral parameters provided by Canıtez and Üçer (1967).
d: Original hypocentral parameters provided by McKenzie (1972).
Mac./Mic.: Original hypocentral parameters provided by Öcal (1959).

I: Canıtez and Üçer (1967).
II: McKenzie (1972).
III: This study.
IV: Ocakoğlu et al. (2005).

to the conclusion that the region experienced a current strike-slip tectonic regime and that the kinematically incompatible E-W-trending normal faulting must belong to an earlier extensional tectonic regime (Figures 3a and 3b). The prominent morphological features of an earlier extensional regime in the region mislead the morphology-oriented studies, suggesting that the younger normal faults were superimposed on the strike-slip faulting (Gözler et al., 1985; Yaltırak, 2002; Koçyiğit, 2005; Ocakoğlu, 2007). The contractional structures that outcropped between İnönü and Bozüyük have also been evaluated as evidence of a compressional period that is thought to have affected the whole of western Anatolia (Koçyiğit, 2005; for a detailed discussion on this issue, see Koçyiğit et al., 1999 and Seyitoğlu, 1999). On the other hand, Altunel and Barka (1998) and this paper (Figure 5) recognize that some of the structures observed in the field (including the contractional structures) are the subsidiary structures of a dominant strike-slip system in the Eskişehir area.

Shallow seismic reflection sections presented in this paper (Figure 12) show the transpressional nature of the Çukurhisar-Sultandere segment. This could be evaluated as a local effect of a left stepping of the right lateral strike-slip segments in the Eskişehir plain (i.e. Kandilli, Bahçehisar, Çukurhisar-Sultandere, and Muttalip segments), but one can argue that this transpressive nature of the Eskişehir Fault Zone is inconsistent with the regional GPS velocity field that increases westward (Reilinger et al., 2006). Recent

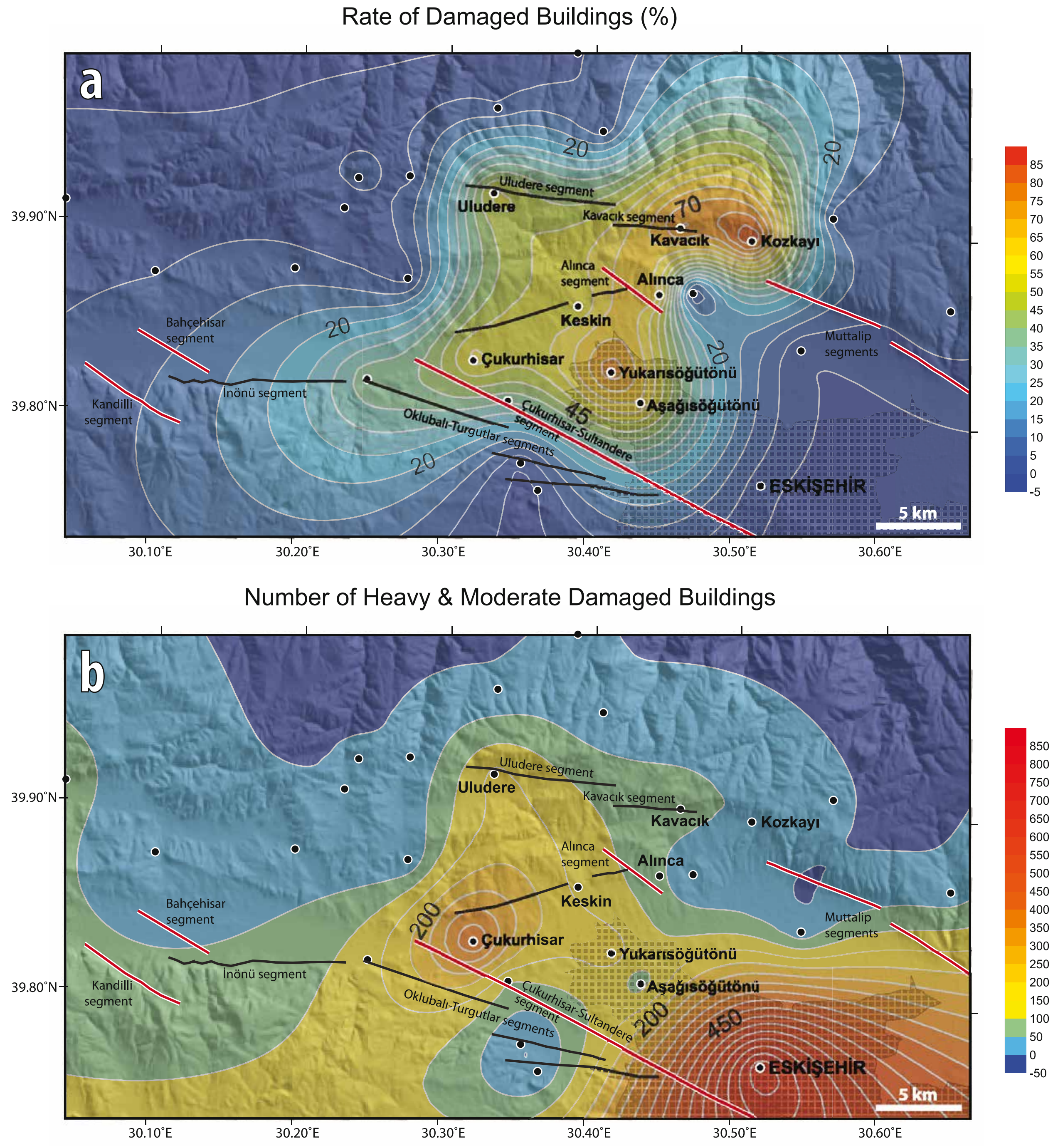

Figure 15. The distribution of buildings damaged during the 1956 Eskişehir earthquake, based on data from Öcal (1959) and Ocakoğlu et al. (2007).

studies in NW Central Anatolia, however, show that the area between the North Anatolian Fault Zone, the Eskişehir Fault Zone, and the Kırıkkale-Erbaa Fault Zone is under NW-SE contraction, as indicated by the Elmadağ-Eldivan and Abdüsselam pinched crustal wedges and the Beypazarı monocline, blind thrusts, and folding axes (Figure 1) (Seyitoğlu et al., 2009; Esat and Seyitoğlu, 2010; Esat, 2011).

It can be further argued that the distinct morphology of the SE part of the Çukurhisar-Sultandere segment noticed in most of the previous studies (see Section 2 and Figure 2) to the south of Sultandere contradicts the transpressive nature of the segment proposed by this paper. In this location, the slopes are dipping north towards the depressed areas, resembling the fault-line scarp of a normal fault (Figure 3).

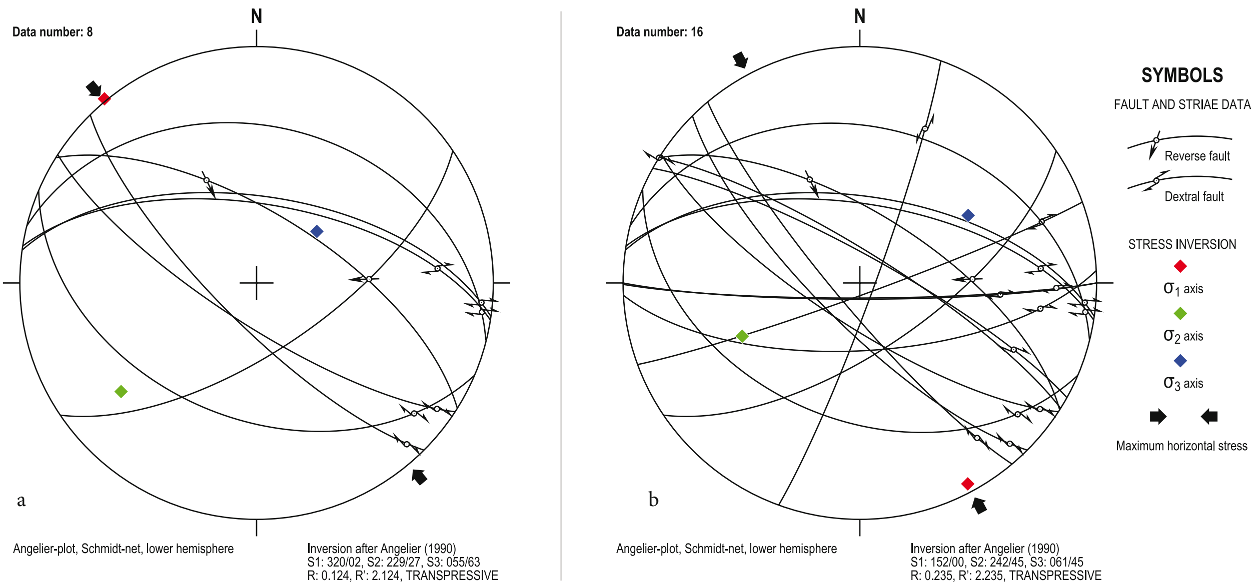

Figure 16. (a) Overall evaluation of the structural data from the focal mechanism solutions indicates transpression. **(b)** Overall evaluation of the structural data from the focal mechanism solutions plus the structural data obtained from the Çukurhisar-Sultandere segment (locations 16 and 17) demonstrates the transpressive character of faulting. SG2PS software (Sasvári and Baharev, 2014) with Angelier's (1990) inversion method was used for the paleostress analysis.

The seismic reflection section G-10 (Figure 11) indicates a clear transpressional feature under the surface. The reverse component of faulting may have influenced the earlier topography and then gravity-induced slips helped to create the recent topography (Figures 17a and 17b). It is known that scarps are not reliable indicators of movement direction. After gravity-induced slips, a period of erosion may cause the inversion of the slope (i.e. an obsequent fault-line scarp) (Figure 17c).

The influence of the focal mechanism solution of the 20.02.1956 (M = 6.5) Eskişehir earthquake (McKenzie 1972) in previous geological studies is higher than the solution of Canıtez and Üçer (1967). An absolute accuracy was attributed to the solution of McKenzie (1972) by

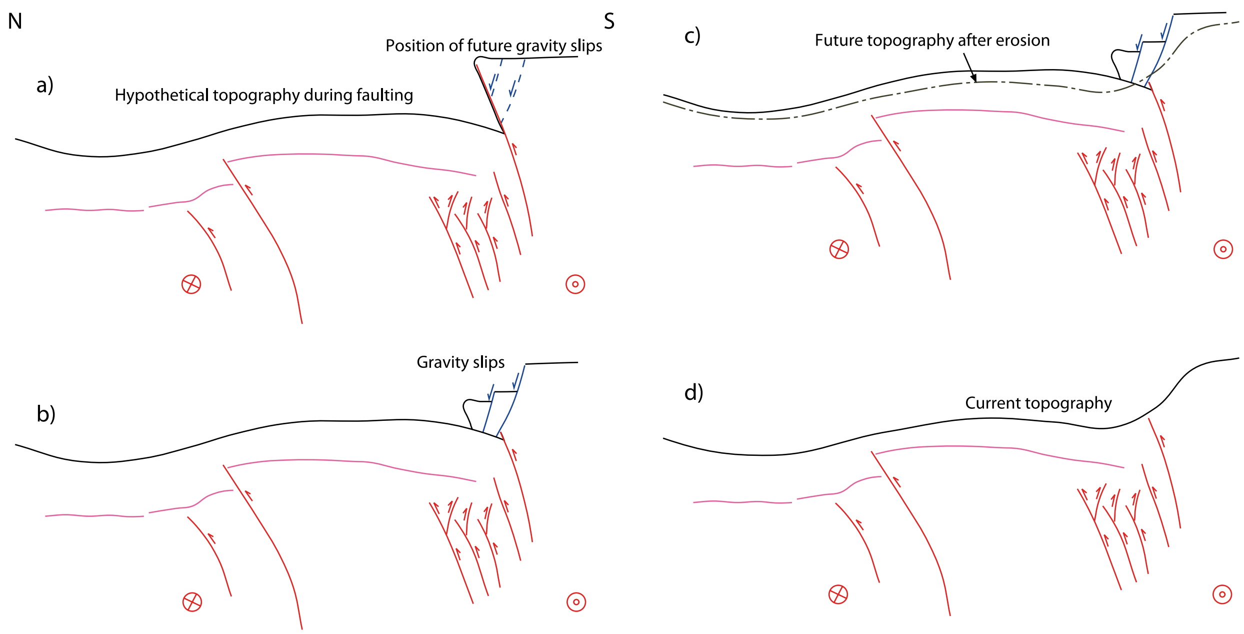

Figure 17. The possible geomorphological evolution of the Çukurhisar-Sultandere segment to the south of the town of Sultandere (not to scale). See Figure 11 for seismic section G-10.

previous studies, which created an impression that there had been an effort to find an appropriate structure in the field. However, the controversies between the epicenter locations and the structures explained in Section 5 led us to question both the epicenter location and the focal mechanism solution of McKenzie (1972). The epicenter of the 1956 earthquake is relocated between Çukurhisar and Sultandere in the middle of the Eskişehir plain (Figure 13), but a reliable focal mechanism solution cannot be obtained. We prefer the focal mechanism solution of Canıtez and Üçer (1967), which is compatible with the structural evaluation in the present paper (Figure 13).

The distribution of epicenters of the earthquakes around Eskişehir does not heavily intensify along the Çukurhisar-Sultandere segment (Figure 13). This can be explained in 2 ways. It could be due to the en echelon nature of segments on the surface having a helicoidal geometry that may join a single basement fault at depth. In such a case, the epicenter locations do not intensify on the surface fault trace. Alternatively, there might be another undiscovered left-stepping segment under the Eskişehir plain whose joint seismic activity around Eskişehir we are observing.

7. Conclusion

In the Eskişehir region, subsidiary structures indicate the position of the main Eskişehir Fault, which has a strike of nearly N60W, and this direction fits with the en echelon bends of the Sarısu River. Thus, the locations of en echelon Bahçehisar and Çukurhisar-Sultandere segments have been postulated. This hypothesis is supported by the seismic reflection sections acquired on the Çukurhisar-Sultandere segment. The results obtained in this paper clearly point to the existence of a nearly 40-km-long fault dominated by positive flower structures. The seismological studies presented in this paper also demonstrate that the 1956 Eskişehir earthquake and recent 1990, 2010, and 2013 earthquakes occurred on or near the Çukurhisar-Sultandere segment, which might be evaluated as a potential seismic hazard source for the Eskişehir settlement.

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