Turkish Journal of Earth Sciences (Turkish J. Earth Sci.), Vol. **12**, 2003, pp. 119-136. *Copyright ©TÜBİTAK*

Timing of Late Holocene Earthquakes on the Eastern Düzce Fault and Implications for Slip Transfer between the Southern and Northern Strands of the North Anatolian Fault System, Bolu, Turkey

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Abstract: Results of trenching across the eastern Düzce Fault document that surface rupture has occurred repeatedly on the fault prior to the 1999 Düzce earthquake, and that offset during previous earthquakes occurred at the same location and with similar amounts and type of slip as that of the 1999 earthquake. The most recent pre-1999 earthquake on the fault occurred about 300 years ago. At least four and possibly five earthquakes (including 1999) have occurred in the past 2100 years. The earthquake recurrence interval ranges from 300 to 800 years. Estimates of cumulative slip on the northern and southern branches of the North Anatolian Fault System (NAFS) (including the Düzce Fault) show that most, if not all, accumulated elastic strain on the fault has been coseismically released at this location. Based on our mapping and palaeoseismic data, it appears likely that the southern and northern strands of the NAFS are structurally and kinematically linked in the vicinity of Bolu by active secondary faults, including the Elmalık and Bakacak faults. These faults extend along the western boundary of the Bolu Basin, between the Düzce Fault and the southern strand of the NAFS. The documented 1999 rupture on the Bakacak Fault and palaeoseismic evidence of previous Holocene displacement strongly suggest that the Bakacak and Elmalık faults transfer slip between the strands of the NAFS.

Key Words: North Anatolian Fault System, slip transfer, active fault, palaeoseismology, Holocene

Düzce Fayının Doğu Kesiminde Geç Holosen Depremleri ve Kuzey Anadolu Fay Sisteminin Güney ve Kuzey Kolları Arasındaki Kayma Transferine Ait Belirtiler

Özet: Düzce Fayı'nın doğusundaki fay kazısı çalışmaları, 1999 Düzce depreminden önce de yüzey kırığı oluştuğunu ortaya koymuştur. Önceki depremlerde meydana gelen yüzey kırıklarının yeri aynı olup, yerdeğiştirme miktarı, tipi ve büyüklüğü 1999 depremindekine benzerdir. 1999 depreminden önce bu fay üzerinde meydana gelen en son deprem 300 yıl önce olmuştur. Bu fay üzerinde son 2100 yıl içerisinde 1999 Düzce depremi de dahil olmak üzere en az 4 veya muhtemelen 5 deprem olmuştur. Bu depremlerin tekrarlanma aralığı 300 ile 800 yıl arasında değişmektedir. Düzce Fayı da dahil, Kuzey Anadolu Fay Sistemi'nin kuzey ve güney kolları üzerindeki kümülatif kaymanın hesaplanması, fay üzerinde biriken elastik deformasyonun tamamı değilse bile önemli bir kısmının bu lokasyonda açığa çıktığını göstermektedir. Paleosismolojik veriler ve yapısal haritalama çalışmaları esas alındığında, Bolu yakınlarında Elmalık ve Bakacak ikincil aktif faylarının Kuzey Anadolu Fay Sistemi'nin kuzey ve güney kolları arasındaki yapısal ve kinematik bağlantıyı kurdukları görülmektedir. Düzce Fayı ve Kuzey Anadolu Fay Sistemi'nin güney kolu arasındaki bu faylar Bolu Havzasının batı kenarı boyunca uzanmaktadır. Bakacak Fayı'ndaki 1999 yüzey kırığı ve Holosen'de yerdeğiştirme olduğunu gösteren paleosismik veriler, Bakacak ve Elmalık fayları ile Kuzey Anadolu Fay Sistemi'nin kolları arasında kaymanın aktarıldığını ortaya koymaktadır.

Anahtar Sözcükler: Kuzey Anadolu Fay Sistemi, kayma aktarılması, aktif fay, paleosismoloji, Holosen

Introduction

The North Anatolian Fault System (NAFS) represents the boundary between the west-moving Anatolian plate and the relatively stable Eurasian plate to the north and extends approximately 1400 km across northern Turkey (Figure 1). The NAFS accommodates most of the plate motion along this plate boundary and is characterised by well-defined seismic activity including historical earthquakes accompanied by surface fault ruptures and prominent geomorphic fault traces.

The NAFS, expressed as a fairly simple single trace east of Bolu, splays into two major branches west of Bolu (Şaroğlu *et al.* 1992) (Figure 1). The southern branch traverses the Lake Abant and Mudurnu Valley areas. The 1944 Bolu-Gerede, 1957 Abant, and 1967 Mudurnu Valley earthquakes occurred along this southern branch of the NAFS. The Düzce Fault is the northern branch of the NAFS and is the source of the 12 November 1999 Düzce earthquake (M=7.2).

According to Öztürk *et al.* (1985), the connection between the Düzce Fault and the southern branch of the NAFS is an extension of the Düzce Fault to the east along the northern margin of the Bolu Basin. Öztürk *et al.* (1985) mapped an active right-lateral strike-slip fault, north of Bolu, called the Çakmaklı Fault. The Çakmaklı Fault consists of at least two parallel faults trending ENE–WSW along the northern boundary of the Bolu Basin, parallel to the southern branch of the NAFS. Öztürk *et al.* (1985) interpreted the Bolu Basin as a pull-apart basin between the southern branch of the NAFS and the Çakmaklı Fault. Although the western end of the Çakmaklı Fault may connect with the Düzce Fault, the relationship between the Çakmaklı and Düzce faults is not well constrained. Barka & Erdik (1993) identified the Düzce Fault extending between Eften Lake and east of Kaynaşlı and concluded that the fault may join the southern branch of the NAFS via a right-releasing stepover involving the Bakacak and Elmalık faults.

Significant slip transfers from the main fault of the NAFS east of Bolu onto the Düzce Fault across a 10- to 15-km-wide stepover (Altunel *et al.* 2000; Barka *et al.* 2001). However, the structural and kinematic connection between the northern Düzce Fault and the southern branch of the NAFS is uncertain. No historically recorded surface rupture connects the Düzce Fault directly to the NAFS.

The Düzce Fault splays from the southern branch of the NAFS in a complex, 10- to 20-km-wide right stepover. The major focus of this study is to define better the structural and kinematic characteristics of the stepover area, define active and potentially active faults within the stepover and develop fault rupture scenarios based on the accumulation and release of seismic strain along the fault system. In addition, we discuss our mapping and present results of palaeoseismic trenching of related faults that appear to transfer slip between the Düzce Fault and the southern branch of the NAFS, across the Bolu structural basin.

Düzce Fault Rupture

The 12 November 1999 Düzce earthquake (M=7.2) produced a 40-km-long surface rupture between Gölyaka in the west and the Bolu Mountains in the east (Figure 2). The rupture was oriented approximately east–west with average right-lateral offset of 3 m and vertical displacement of up to 3.5 m. Maximum right-lateral offset is 5 ± 0.3 m near the village of Güven. Surface rupture occurred within a narrow zone of deformation typically between 2 and 5 m wide.

Prior to the 12 November 1999 earthquake, the Düzce Fault was identified by Barka & Erdik (1993) as a possible fault hazard in an unpublished consulting report. In that report, Barka and Erdik (1993) identified the Düzce Fault as a potentially active fault extending between Eften Lake and east of Kaynaşlı. As noted by Barka & Erdik (1993) and more recently by Akyüz *et al.* (2000, 2002), the Düzce Fault is well expressed geomorphically along much of its mapped length. Right-lateral offset of previously deflected streams demonstrates older, repeated earthquake ruptures.

The 1999 Düzce rupture terminates in extremely rugged, steep terrain in its eastern end. Based on interpretation of topographic maps and SPOT imagery we identified no significant extension of the Düzce Fault further east of the rupture end. However, according to Çakır *et al.* (2003), GPS and InSAR data suggest that the rupture extends about 15 km further east at depth.

Results of Palaeoseismic Trenching

In order to obtain detailed information on the style and frequency of surface-faulting earthquakes, we excavated

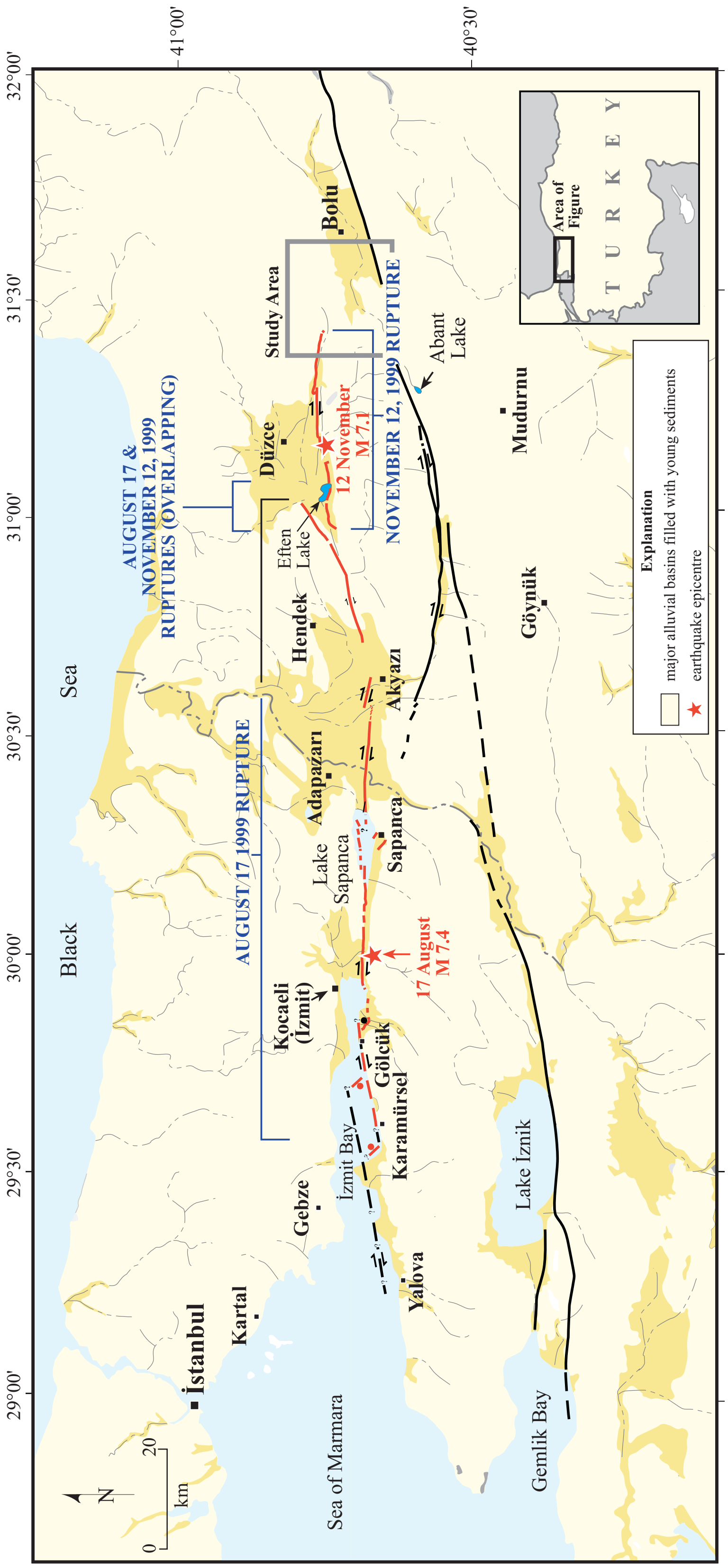


Figure 1. Map of northwestern Turkey showing the study area and ruptures of the 17 August 1999 and 12 November 1999 Düzce earthquakes.

palaeoseismic trenches on the Düzce, Bakacak and Elmalık faults (Figure 2). The trenches were excavated 1 to 2 m deep and 5 to 20 m long, across the fault traces. In conjunction with the trench investigations at these sites, we mapped surface rupture-related features at each site prior to trenching. Age estimates of the surficial deposits exposed within the trenches are based on stratigraphic relationships and radiocarbon analyses on selected charcoal fragments collected from deposits. Results of the age dating are presented in Table 1.

The 1999 Düzce Rupture

Trench T-1. Trench T-1 across the Düzce rupture is located in an open, grassy field near Kaynaşlı (GPS coordinates N40°46.524', E031°20.025'; Figure 2). The fault rupture at this location trends approximately east–west (090°) and is characterised by a well-defined, narrow (<2 m wide) zone of south-facing scarps and minor en-echelon mole tracks up to 0.5 m high. At this site a north–south-trending wooden fence is offset in a right-lateral sense approximately 2 ± 0.5 m.

The 11-m-long and up to 2.5-m-deep trench was located about 15 m west of the fault offset fence. At this location, Trench T-1 crosses a 1.5-m-wide rupture zone characterised by a 0.46-m-high, main south-facing scarp with an associated 0.12-m-wide fissure fill and a parallel, minor (0.05-m-high) north-facing scarp. The 1999 fault rupture is clearly expressed within the trench as an approximately 0.2-m-wide fissure fill at the base of the trench (Figure 3). This fill, characterised by unbedded, disordered gravel fragments and loose sand, bells upward and is bounded by abrupt faulted edges.

Total structural relief on the basal bluish-grey sand across the trench is approximately 1 m (Figure 3). The structural relief includes vertical offset from the 1999 earthquake and an older earthquake that produced 0.45 m of vertical offset of the bluish-grey sand at the southern end of the trench. The buried 0.45 m offset is located approximately 2 m south of the 1999 rupture within the southern end of the trench. At this location the faulted bluish-grey silty sand is overlain by unfaulted, moderately well-bedded fine sand.

Age estimates of the penultimate event on the Düzce Fault prior to the November 1999 earthquake are based on two radiocarbon analyses on charcoal fragments collected from deposits near the base of the trench (samples T1-1 and T1-3; Figure 3). Detrital charcoal samples were collected and analysed from the faulted fine-grained bluish-grey sand at the base of the trench and overlying unfaulted fine sand. Charcoal samples T1-1 and T1-2, analysed from the lowermost faulted deposit, yielded calibrated ages of about 4000 years before the present (Table 1), indicating that at least one prior earthquake occurred in the past 4000 years before the 1999 event. Unfortunately, we were unable to bracket the age of the penultimate event because charcoal sample T1-3 from the overlying unfaulted deposit was not sufficient for dating.

The significance of the stratigraphic relations exposed in Trench T-1 include documentation of at least one, and possibly more, Holocene surface-rupture events on the Düzce Fault prior to the November 1999 earthquake. In addition, the buried fault scarp and discrete vertical offset of older deposits overlain by unfaulted younger deposits is similar to the amount of vertical offset during the 1999 rupture suggesting that the penultimate event produced surface rupture in roughly the same location and of the same amount and style as the 1999 rupture.

Trench T-2. The second fault trench is located in an open field, approximately 500 m east of Trench 1 (Figure 2). The site is characterised by an 8.5-m-wide zone of en-echelon south-facing scarps and open fissures produced by the 1999 Düzce earthquake. An adjacent north–south-trending post-and-wire fence is offset approximately 2 m in a right-lateral sense. An older, broad, south-facing scarp also is present at the site indicating pre-1999 fault activity. The trench site was selected because of the presence of the older south-facing scarp, well-defined fissure fills along the fault trace, and of the adjacent offset fence, which provides an accurate measurement of horizontal slip in the 1999 rupture.

Within Trench T-2, interbedded alluvial deposits, including sand and gravel flood deposits and silty overbank deposits from the nearby Asarsu River, are warped into a broad south-facing scarp and are locally faulted (Figures 4 & 5). The 1999 fault rupture is expressed in the trench as a series of fissure fills and discrete faults. These fissures are present in the centre of the trench and extend to the base of the trench. The fissure fills are characterised by unbedded, disordered sand with gravel and are bounded by faults that clearly truncate bedding.

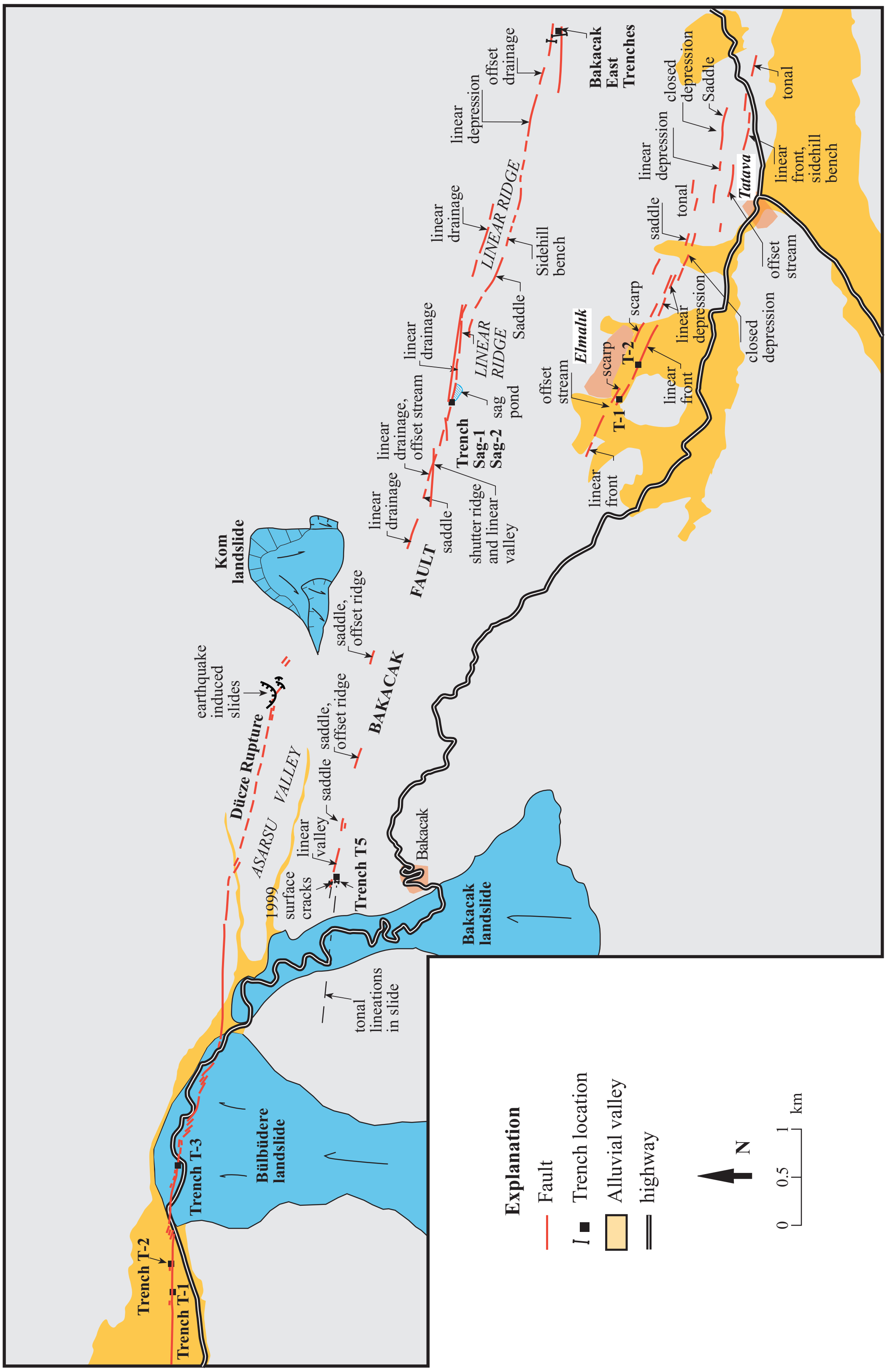
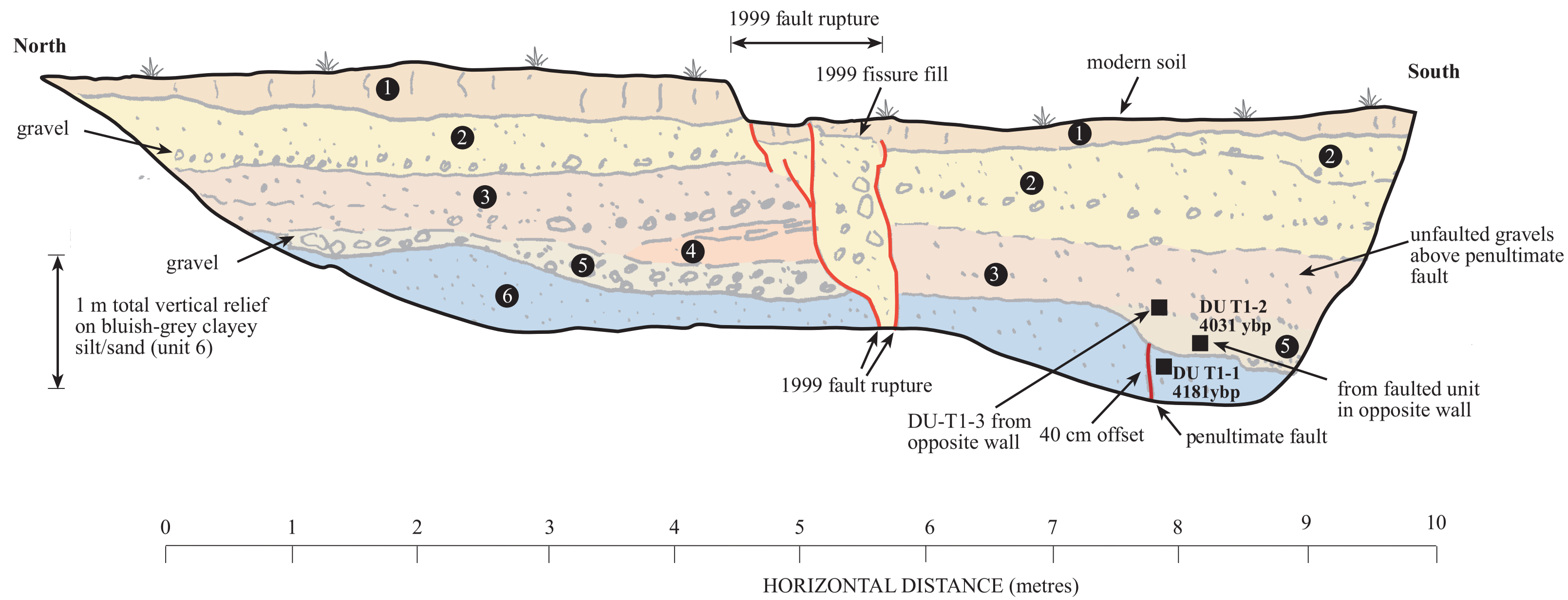


Figure 2. Map showing Düzce Fault rupture, geomorphic mapping of Bakacak and Elmalik faults for this study, and palaeoseismic trench locations.



Explanation

- 1 soil; clayey sand, organic rich, blocky structure, poorly sorted sand with intraspaced rounded pebbles and gravels (soil)
- 2 gravelly, silty sand with fine clay; fine to coarse poorly sorted sand, pebbles and gravels (stream deposits)
- 3 gravelly, silty sand with fine clay; fine to coarse poorly sorted sand, pebbles and gravels (stream deposits)
- 4 silty sand (10YR 4/3); fine to medium, moderately sorted (overbank deposit)
- 5 gravel and sand (stream gravel deposits)
- 6 clayey silt to clayey sand, bluish-grey, fine-grained, massive (stream deposit)
- ■ location of charcoal sample
- **ybp** age in years before present

Figure 3. Düzce Fault, Trench T-1

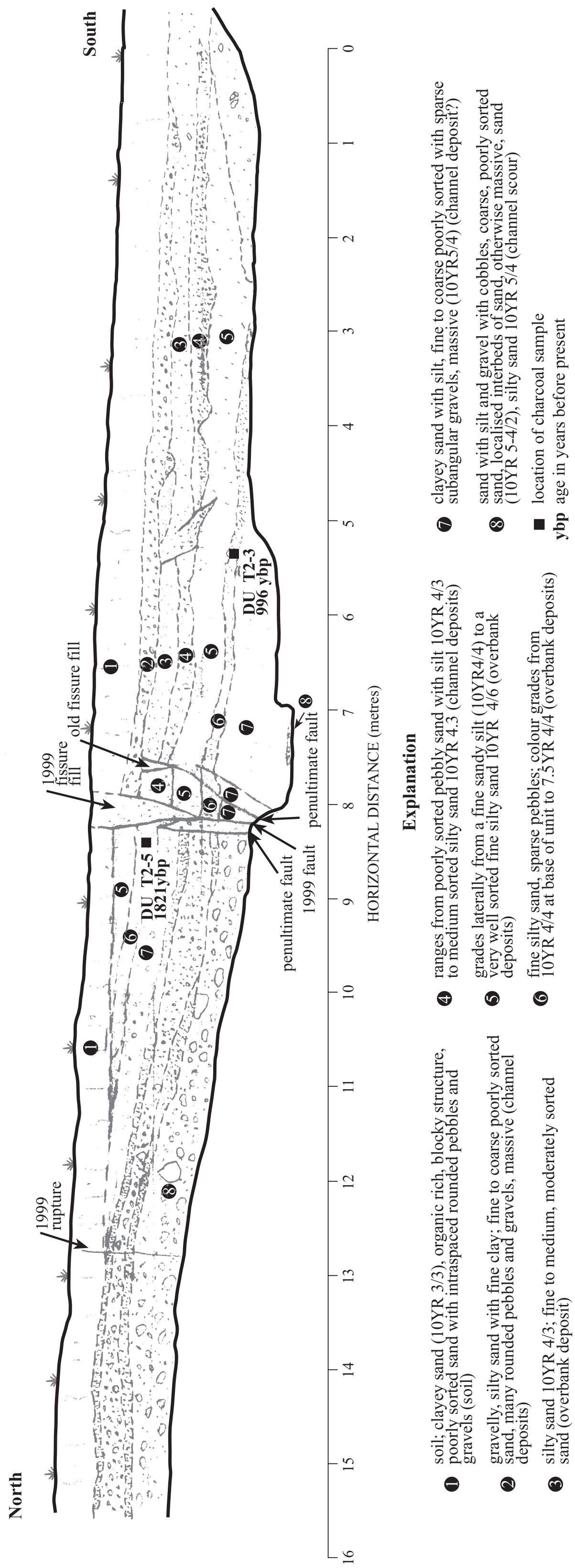
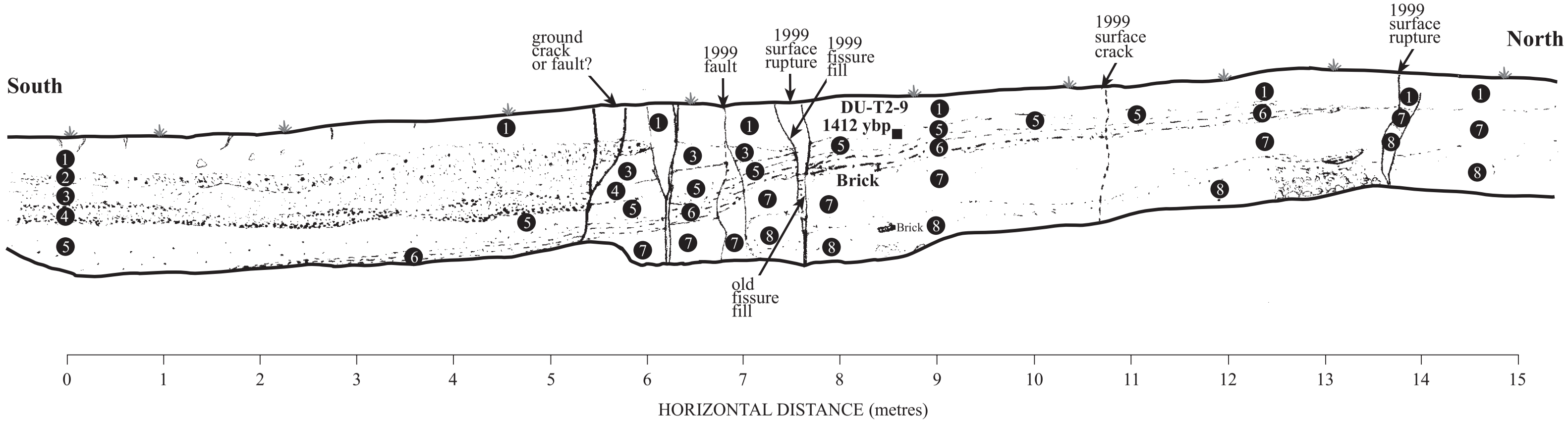


Figure 4. Düzce Fault, Trench T-2, east wall.



Explanation

1. soil; clayey sand (10YR 3/3), organic rich, blocky structure, poorly sorted sand with intraspaced rounded pebbles and gravels. Local fill fissures.
2. gravelly, silty sand with fine clay; fine to coarse poorly sorted sand, many rounded pebbles and gravels, massive (channel deposits)
3. silty sand (10YR 4/3); fine to medium, moderately sorted sand (overbank deposit)
4. ranges from poorly sorted pebbly sand with silt (10YR 4/3) to medium sorted silty sand (10YR 4.3) (channel deposits)
5. fine silty sand, sparse pebbles; colour grades from10YR 4/4 at base of unit to 7.5YR 4/4 (overbank deposit?)
6. grades laterally from a fine sandy silt (10YR4/4) to a very well sorted fine silty sand (10YR 4/6) (overbank deposit?)
7. clayey sand with silt (10YR5/4), fine to coarse poorly sorted with spase subangular gravels, massive (channel deposit?)
8. sand with silt and gravel with cobbles, coarse, poorly sorted sand, localised interbeds of sand, otherwise massive, sand (10YR 5-4/2), silty sand (10YR 5/4) (channel scour)

■ Location of charcoal sample

ybp age in years before present

Figure 5. Düzce Fault, Trench T-2, west wall.

Table 1. Radiocarbon dates from trenches across the November 1999 Düzce rupture, Bakacak Fault and Elmalık faults.

Field Sample No.	Laboratory Sample Number	^{14}C Date[1]	Dendrocorrected Age
Düzce Rupture Trench			
DU-T1-1	69286	3820 ± 40	4181 ± 75/-32
DU-T1-2	69179	3700 ± 40	4031 ± 47/-98
DU-T2-3	69174	1070 ± 50	966 ± 85/-34
DU-T2-5	69175	1870 ± 40	1821 ± 48/-89
DU-T2-9	69176	1540 ± 50	1412 ± 106/-61
DU-T3-3	69284	210 ± 40	166 ± 119/-162
DU-T3-5	69177	270 ± 50	305 ± 120/-17
DU-T3-6	69285	290 ± 50	310 ± 121/-16
DU-T3-7	69178	2110 ± 40	2079 ± 67/-77
Bakacak Fault			
BAK-T2-2	69180	1350 ± 50	1287 ± 12/-26
Elmalık Fault			
ELM-T2-1	69287	3040 ± 40	3312 ± 22/-144
ELM-T2-5	69181	4140 ± 50	4644 ± 178/-111

(1) The quoted age is in radiocarbon years using the Libby half-life of 5568 years.
Notes: Sample preparation backgrounds have been subtracted, based on measurements of samples of ^{14}C-free coal. Backgrounds were scaled relative to sample size.
Comment: The material dated was acid-base-acid treated charcoal.

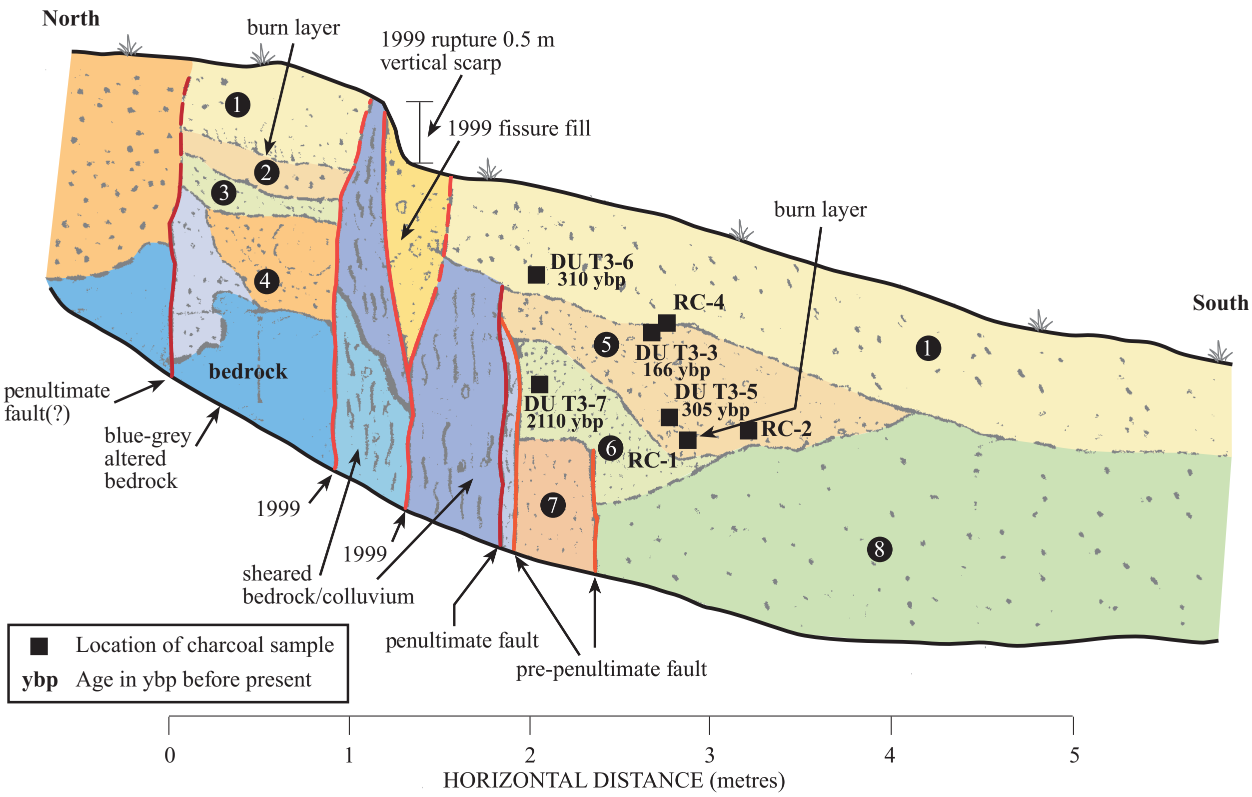
Total vertical structural relief on the basal faulted gravel across the trench is approximately 1.5 m, likely reflecting a buried fault scarp including vertical offset from the 1999 earthquake and at least one prior earthquake. Evidence for one or more prior earthquakes also includes the presence of buried fissure fills. The 1999 earthquake produced only minor vertical displacement at the ground surface at this site while the lower gravels exposed in T-2 are vertically separated by 1.5 m. This suggests multiple earthquakes at the site to produce the cumulative vertical offset or it could represent: (1) a slight change in fault surface rupture pattern between the 1999 and penultimate events; (2) a larger penultimate earthquake; or (3) the juxtaposition of palaeotopographic differences within depositional units.

Trench T-2 provides direct stratigraphic evidence for at least one and probably two pre-1999 earthquakes. The timing of these events is based on radiocarbon samples of charcoal collected from deposits within the trench (samples DU-T2-3, DU-T2-5, and DU-T2-9; Table 1; Figures 4 & 5). Charcoal sample DU-T2-5 was collected from an older fissure fill deposit and yielded a calibrated age of 1821 ybp (Table 1; Figure 4). The older fissure fill is similar in size to the fissures produced by the 1999 earthquake at this site suggesting that the two earthquakes may be of similar size. The older fissure fill appears to be faulted by another pre-1999 earthquake (i.e., the penultimate event). Charcoal sample DU-T2-9 was collected from an unfaulted deposit overlying the faulted fissure fill on the opposite trench wall (Figure 5) and yielded a calibrated age of 1412 ybp. Thus, the stratigraphic relationships and age results suggest at least one and probably two pre-1999 earthquakes in the past 1821 years. Assuming that the fissure fill closely approximates the age of the earthquake, the pre-penultimate event occurred about 1800 years ago. The penultimate event occurred some time between 1400 and 1800 years ago, although these age constraints are based on only two dates and, therefore, must be regarded with significant uncertainty.

As in Trench T-1, the stratigraphic relationships exposed in Trench T-2 provide documentation for at least one, and probably two, pre-1999 earthquakes in the past 1800 years. In addition, the presence of a buried fault scarp and older fissure fills overlain by unfaulted younger deposits provides evidence that prior earthquakes produced rupture in the same locations, with a similar style of deformation as the 1999 rupture, although the amount of vertical slip during the pre-1999 events may have been larger than that caused by the 1999 event.

Trench T-3. The third trench locality on the Düzce Fault is in a small orchard at a bend in the old road to Bolu, about 1 km east of Trench 2 (Figure 2). At this location, a prominent east–west-trending, south-facing, pre-existing 2-m-high scarp is preserved near the bend in a small stream. Rupture associated with the 1999 earthquake is located near the middle of the scarp and consists of a single vertical scarp with approximately 0.5-m down-to-the-south vertical offset. Trench T-3 is an approximately 6-m-long, 1.5-m-deep trench across the pre-existing scarp and the 1999 Düzce Fault rupture (Figure 6).

The trench site was selected because of the presence of a pre-existing fault scarp, suggesting that previous earthquakes had ruptured in the same location. Evidence for at least three and possibly four prior events is documented at this location (Figure 6). Within Trench T-3, several distinct packages of colluvium are in fault



Explanation

1. silt, gravelly, dry, brown (10YR 5/3), <2% gravel with subangular clasts (colluvium)
2. clay, sandy, yellowish brown (10YR 5/4), (colluvium)
3. sand, gravelly, clayey, reddish brown (5YR 5/4), poorly sorted, subangular grains (old colluvium)
4. clay, sandy, yellowish red (5YR 5/4), poorly sorted (old colluvium)
5. gravel, silty to silt, gravelly, brown (10YR 5/3), poorly sorted with angular to sub-angular clasts, burn layer near base (colluvium)
6. gravel, clayey, brown (7.5 YR 4/4), poorly sorted (colluvium)
7. clay, sandy to sand, clayey, yellowish brown (10YR 5/4), (colluvium?)
8. clay, silty, gravelly, brown (10YR 4/3), sub-angular clasts <5% (colluvium)

Figure 6. Düzce Fault, Trench T-3.

contact with bedrock and are locally internally faulted (Figure 6). The 1999 fault rupture is expressed in the trench as a near-vertical fault that extends to the ground surface with an associated fissure fill.

The timing of the penultimate event and pre-penultimate event at this site is based on four radiocarbon dates on charcoal collected from the faulted colluvial units (samples T3-3, T3-5, T3-6, T3-7; Figure 6; Table 1). Sample T3-6 was collected from the youngest colluvial unit (unit 1) and yielded a calibrated age of 290 ybp. The colluvium was offset by the 1999 rupture but overlies the penultimate fault rupture and, thus, provides a minimum age for the penultimate event. Samples T3-3 and T3-5 were collected from the second oldest colluvial unit (unit 5) and yielded calibrated ages ranging from 166 to 305 ybp. The older colluvium is offset by the penultimate event and, thus, provides a maximum age for the penultimate event of 305 years ago. From the radiocarbon dates on units 1 (unfaulted) and 5 (faulted), we infer that the penultimate event occurred approximately 300 ± 50 years ago and triggered formation of a colluvial wedge (i.e. unit 1) immediately following the earthquake. Colluvial unit 5 shows a minimum vertical displacement of at least 30 cm during the penultimate event; the upper part of the offset was eroded during the development of the unit 1 colluvial wedge. Thus, the amount of vertical separation during the penultimate event at the site is comparable to the vertical separation (0.5 m) produced by the 1999 rupture.

The pre-penultimate event is constrained by the age of the next oldest colluvial deposit (unit 6). This colluvium appears to be an older scarp-derived colluvial wedge. The colluvium subsequently was offset at least once and possibly twice by surface faulting events that pre-date the penultimate event. These events produced vertical separations of about 0.5 m each (if two events) or 1 m (if one event). Sample T3-7 was collected from colluvial unit 6 and yielded a calibrated age of 2079 ybp (Table 1). Thus, at least three, and probably four, events can be documented in the past approximately 2000 years at this site. If we conclude that colluvial unit 6 is itself a scarp-derived colluvium, it suggests that it formed in response to a fifth surface-faulting event about 2100 years ago. In addition, other events may have occurred along the northern margin of the fault zone where stratigraphic relationships are not available to constrain their age. Thus, the stratigraphic relationships and age dates at Trench T-3 document four and possibly five surface-faulting events in the past approximately 2100 years. The youngest event occurred in 1999, the oldest event occurred about 2100 years ago to form the unit 6 colluvial wedge. The penultimate (second oldest) event occurred about 300 years ago. The third and fourth (?) events occurred some time between about 2100 and 300 years ago. Based on the results from Trench T-2, at least one and may be both of these events occurred between about 1800 and 1400 years ago. Other young events also may have occurred along the northern margin of the fault zone. We conclude from these relationships that the recurrence interval between surface-faulting events is at least 300 years, and may range from 300 to a maximum of 800 years. Using the amount of vertical separation as a proxy for the style and amount of surface displacement, it appears that the penultimate and pre-ultimate events at the site were similar in size to the 1999 Düzce earthquake.

The Bakacak Fault

The Bakacak Fault extends southeastward from the Düzce Fault to several kilometres west of Bolu (Figure 2). The total mapped length of the Bakacak Fault is 10 to 15 km. Between the Düzce and Bakacak faults, the Bülbülderesi and Bakacak landslides conceal the structural connection between these two faults. Juxtaposed bedrock units indicate that the Bakacak Fault is a major structural discontinuity along which significant past displacement has occurred. As discussed below, movement along the Bakacak Fault appears to have continued through the Quaternary.

Although located within largely mountainous terrain, the Bakacak Fault is geomorphically well expressed locally along much of its length (Figure 2). Analysis of aerial photography and field reconnaissance conducted for this study provides documentation of numerous geomorphic features along the fault that are indicative of active strike-slip faulting. These features include linear drainages, troughs, offset ridges, right-laterally deflected drainages, scarps, topographic saddles, and closed depressions. The western end of the Bakacak Fault is not well constrained because the fault in this area is largely within landslide deposits of various ages and relatively continuous fault-related features cannot be traced through the disturbed ground.

Based on our air-photo interpretation and field reconnaissance, the Bakacak Fault appears to consist of several discontinuous, and possibly en-echelon fault segments. The segments are 3 to 5 km long and have varying degrees of geomorphic expression. It is not known if the variation in geomorphic expression reflects variation in fault activity or variation in preservation of the fault trace due to differential erosion, vegetation, and landslides. The western 3-to 5-km section of the fault overlaps with and forms a 1-km-wide right-stepover to the Düzce Fault segment that ruptured in 1999 (Figure 2). The westernmost 1 to 2 km section of the fault is well expressed geomorphically by a linear drainage, side-hill benches and offset linear ridges. The offset linear ridges, in particular, cannot be produced by fault-line erosion, and strongly indicate significant Quaternary right-lateral displacement along the fault.

The central segment of the fault is also well expressed. Geomorphic features in this area include a large sag pond (Figure 2) and fault-bounded linear ridges, topographic saddles and linear drainages. The eastern 3- to 5-km section of the Bakacak Fault is not as well expressed. An apparent right-deflected drainage and a linear depression occur along the eastern part of the fault. The fault location in this area is based primarily on tonal lineaments.

The 1999 Düzce earthquake produced minor faulting along the western part of the Bakacak Fault. Figure 7 is a photograph showing the type of surface faulting. The location of observed 1999 ground cracking is shown on Figure 2. The trend of ground cracking at the site (290˚) is consistent with the trend of the Bakacak Fault. This, in conjunction with the straight and linear character of the cracks, and the occurrence of the cracks on an elongated sidehill bench, suggest that the cracking was caused by minor movement on the Bakacak Fault. The direction of vertical separation along the crack varied along the trend and evidence of landsliding was observed at the crack location or on the hillside below the crack. Thus, we conclude that the cracks represent minor rupture along the Bakacak Fault.

Palaeoseismic trenches were excavated along the Bakacak Fault at three locations (Figure 2). These three trench sites are located along the western, central and eastern segment of the fault, respectively, and provide information on the recency of faulting and the nature of fault displacement (i.e. secondary or primary rupture). Below we describe in more detail the trench across the 1999 surface displacement on the western Bakacak Fault and trench information from the central Bakacak Fault that provides constraints on the timing of faulting.

Trench TP-5. Trench TP-5 was a small, hand-excavated trench located across a 1999 crack zone on a ridge sideslope bench (Figure 8). The trench was extended to a depth of 0.6 m. Stratigraphy in the trench consisted of subhorizontally layered topsoil and colluvium over weathered metamorphic bedrock. A 0.2-m-wide zone of steep to vertical fractures and fissures was exposed in the trench wall at the location of the 1999 ground cracks and extended for the full depth of the trench. The trend of the fractures was 290º (the same as the ground trace), and dipped vertically or nearly vertically with a slight southward dip. The fractures appear to disrupt the colluvial deposits overlying bedrock. The fractures were locally in-filled with surficial soil.

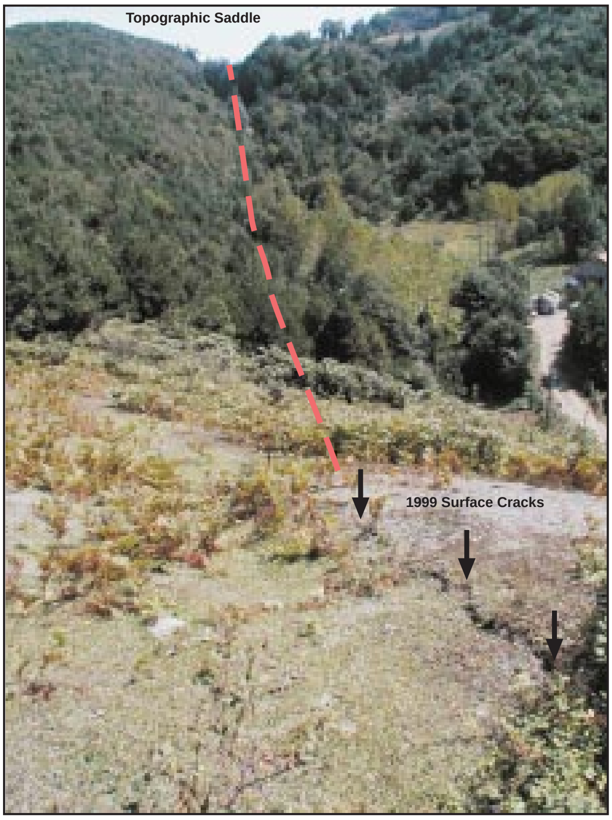
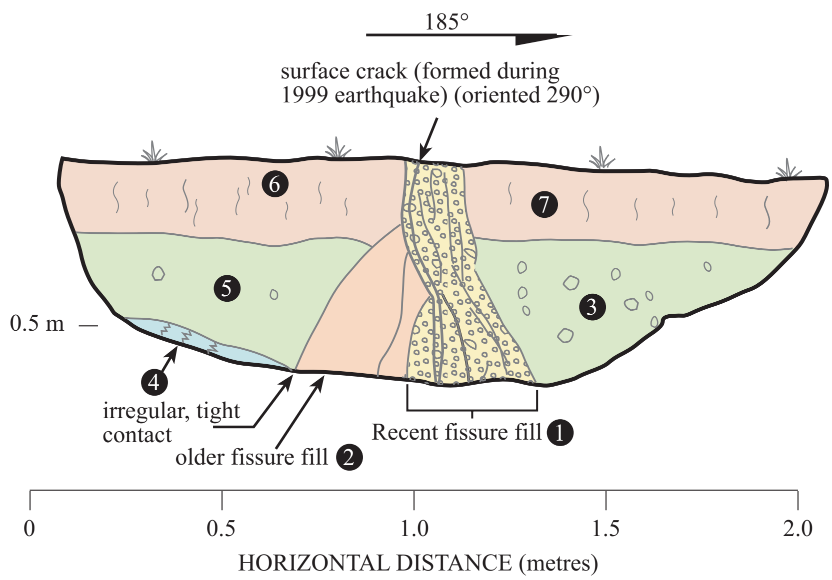


Figure 7. View to east along trend of the Bakacak Fault with 1999 surface cracking in foreground. Note topographic saddle in distance formed by the Bakacak Fault. Location of hand-dug trench shown in Figure 8. The red dashed line shows inferred trace of the Bakacak Fault.

A possible older fissure fill soil, consisting of stiff blocky clay with a faint steep, platy fabric, occurs adjacent to the 1999 fissure zone. The size of the possible older fissure fill is similar to the 1999 fissure zone. However, the older fill appears to be a true distinct deposit (i.e. fissure fill) rather than simply a zone of fractured and fissured pre-existing sediment. Thus, the older fissure fill may reflect a larger slip event than the 1999 faulting at the site. No datable materials were found in Trench T-5 that could be used to date the prior earthquake.

The direction of ground cracking at the TP-5 location (290º) is consistent with the trend of the Bakacak Fault. The sense of apparent vertical displacement changed along the trend indicating that the ground cracking is not the result of incipient slope failure along the fault. This, in conjunction with the straight and linear character of the cracks, and occurrence on an elongated side-hill bench, suggest that the cracking was caused by sympathetic movement or triggered slip on the Bakacak



Explanation

1 recent fissure fill: red-brown fissured, blocky clay; plastic, medium stiff, numerous open cracks, damp

2 older (?) fissure fill: similar to 1, more stiff, less to no open cracks

3 old colluvium, mottled red-brown and grey, sandy, silty clay, very stiff to hard, damp to dry, metamorphic rock fragments

4 weathered metamorphic bedrock, highly to completely weathered, grey with oxidised orange streaks, damp to dry

5 old colluvium, grey, silty clay with oxidised streaks, stiff, few small oxidised metamorphic rock fragments, dry

6 soil a-horizon, brown, sandy silt/clay, medium stiff, moist

7 soil a-horizon, light grey, clayey silt, very stiff to hard, dry

* No charcoal found in test trench

Figure 8. Hand-dug trench across 1999 cracks along the Bakacak Fault.

Fault. The trench indicates that past surface faulting events have occurred at this location along the Bakacak Fault, and, thus, the Bakacak Fault is a Holocene-active fault. The Bakacak Fault also juxtaposes different packages of colluvium indicating that significant cumulative right-lateral slip has occurred in the past.

Two trenches were excavated across a large linear valley and sag pond along the central Bakacak Fault (Figure 2). The sag pond is interpreted as a small right-releasing stepover in the fault trace. The trenches were extended across the valley and both margins of the pond. Trench sag-1 is 25 m long and 1.5 to 3 m deep and crossed the northern margin of the sag pond. The trench exposed well-bedded clay, silt and organic layers that appear to be unfaulted. Trench sag-2 was 1.5 to 2 m deep, and extended for 58 m across the central and southern part of the depression. Trench sag-2 shows strong evidence for a fault along the central part of the sag pond depression. An apparent faulted fissure fill is present along a pre-existing bedrock fault trace (Figure 9). The fissure fill extends up into the near surface soils.

Weakly developed topsoil above the fissure fill exhibited a subhorizontal soil parting structure, apparently formed by settlement above the fissure fill. Radiocarbon sample T2-2 was collected from a faulted silty clay deposit adjacent to the fissure fill and yielded a dendrocorrected age of 1287 + 12/-16 ybp. Thus, the central segment of the Bakacak Fault exhibits evidence of Late Holocene surface faulting with the most recent event occurring within the last 1280 years.

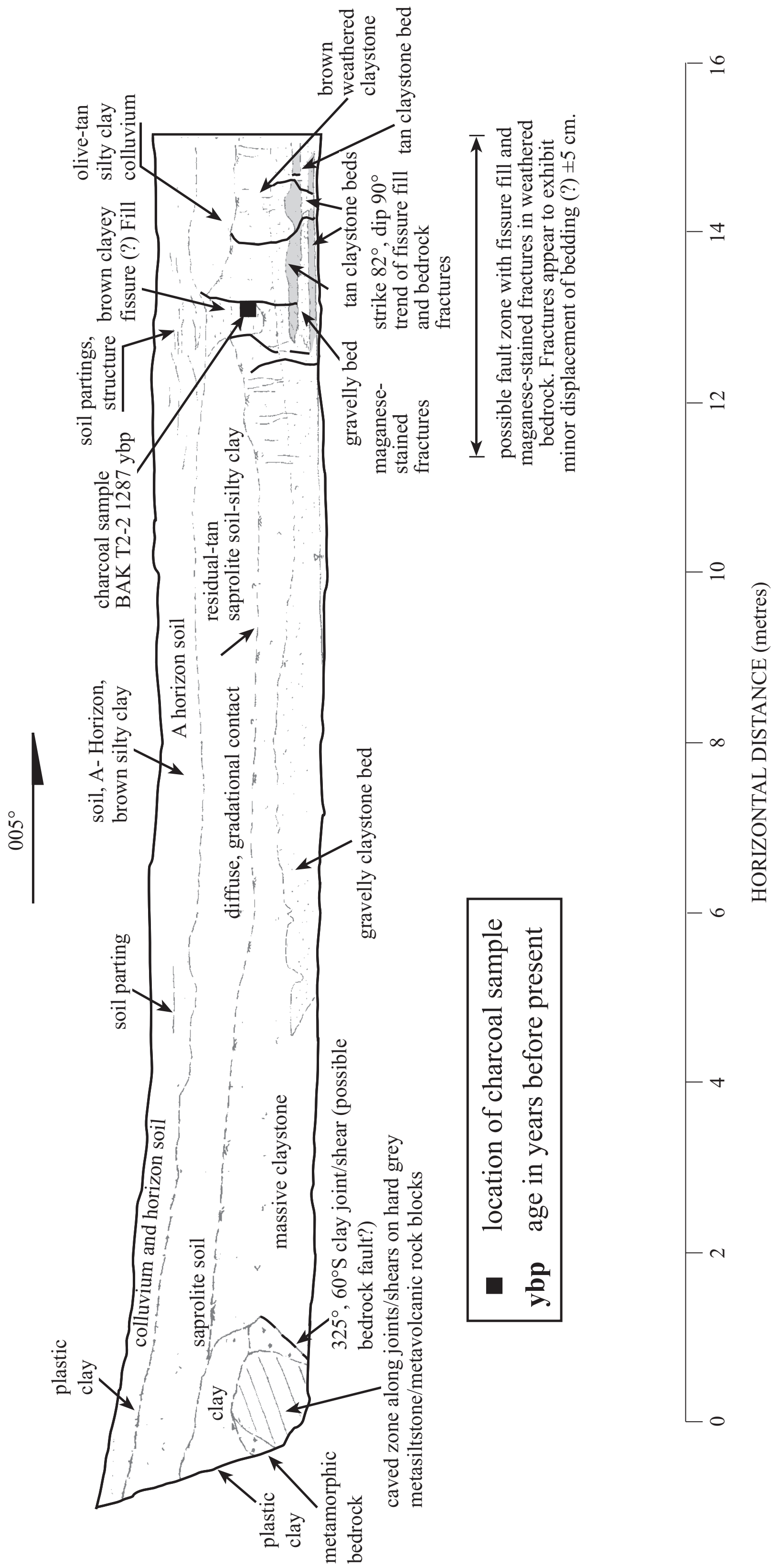


Figure 9. Bakacak Fault Trench Sag-2.

The Elmalık Fault

The Elmalık Fault is a northwest–southeast-trending fault that extends for a distance of about 15 km into the Bolu Basin (Figure 2). The Elmalık Fault is well expressed as a geomorphic feature along the western 8 km of the fault but is less well expressed along its eastern 7 km length within the Bolu Basin. The fault may die out within the basin and form a 1- to 2-km-wide right stepover to the southern branch of the NAFS or it may merge with the Bolu Fault segment along the southern margin of the Bolu Basin.

Two trenches (Trenches T-1 and T-2) were excavated across the Elmalık Fault. The trenches were sited across linear hillfronts and drainages along geomorphically well-defined segments of the fault. Trench T-1 was sited across eroded scarps or breaks-in-slope between slightly elevated stream terraces and modern basin alluvium. Trench T-2 was located at the base of a linear hill along the southeastward projection of the fault segment investigated by Trench T-1. Together, these trenches provide information regarding past earthquakes and fault geometry of prominent segments of the Elmalık Fault.

Trench T-1 was located across a 1- to 1.5-m-high, northwest-trending break-in-slope coincident with a photolineament. The break-in-slope appears to be an eroded north-facing fault scarp along a splay of the Elmalık Fault. The trench was excavated to a depth of between 1.5 and 2.5 m, and was 13 m long. Stratigraphy in the trench consisted of interbedded, partly consolidated, old clay and gravel alluvium (Pleistocene), young clayey alluvium (Holocene), and fill. Two prominent, north-dipping faults, and numerous secondary fault splays, cut through the old alluvium in the central part of the trench. Each fault zone is about 1 m wide, and includes numerous individual and anastomosing splays that fan upwards through the old alluvium. Slickenlines and mullions on fault planes exhibit rakes between about 15° and 45° from horizontal indicating that the last episodes of movement along the faults included oblique displacement with components of both horizontal and vertical displacement.

Trench T-2. Trench T-2 was excavated across the south margin of Elmalık valley at the base of a linear hillfront (Figure 2). The trench was oriented in a north–south direction, oblique to a geomorphically well-expressed segment of the Elmalık Fault and was 1.5 to 2 m deep, and 28 m long. Stratigraphy consisted of extensively faulted and deformed older alluvium in the southern part of the trench and flat lying and apparently undeformed younger clay alluvium in the north part of the trench. Fifteen separate fault splays were identified cutting the old alluvium in an 18-m-wide zone of deformation. Fault splays juxtaposed different alluvial beds and/or disrupted and tilted individual beds (Figure 10). The most prominent, main fault consisted of four separate subparallel splays within a 1-m-wide zone in the southern part of the trench. The main fault bounded a distinct gravel bed that was juxtaposed against a carbonate-rich clay bed.

Fault splays included clayey seams and zones of imbricated gravel. Liquefaction injection dykes penetrated along, and partially assimilated, two of the fault splays within the main fault zone. Displacements along faults appear to include both lateral and vertical movements. Multiple colluvial wedges and fissure fills were identified above many of the faults indicating a complex history of multiple earthquake events. Vertical offsets and palaeoscarps in old alluvium and overlying colluvial wedge deposits ranged between about 10 cm and 1 m. Displaced alluvium and colluvial wedges in the trench provide evidence for at least two or three separate palaeoearthquakes.

Two charcoal samples from Trench T-2 were submitted for radiocarbon dating: sample T2-1 from the base of a faulted clay bed in the northern part of the trench and Sample T2-5 from an unfaulted clay layer that overlies a faulted colluvial wedge and strand of the main fault zone. Sample T2-1 gave a calibrated age of 3040 years, and Sample T2-5 gave an age of 4140 years. These two dates suggest that at least two different palaeoearthquakes produced faulting in the trench: one event more recent than 3040 years ago, and another event more than 4140 years ago.

Discussion and Conclusions

Results of palaeoseismic trenching show that repeated pre-1999 surface-faulting events have occurred along the Düzce Fault. These events occurred within a narrow zone along a pre-existing fault. Similar amounts of vertical separation and the size of fissure fills suggest that the prior events were comparable in size to the 1999 event

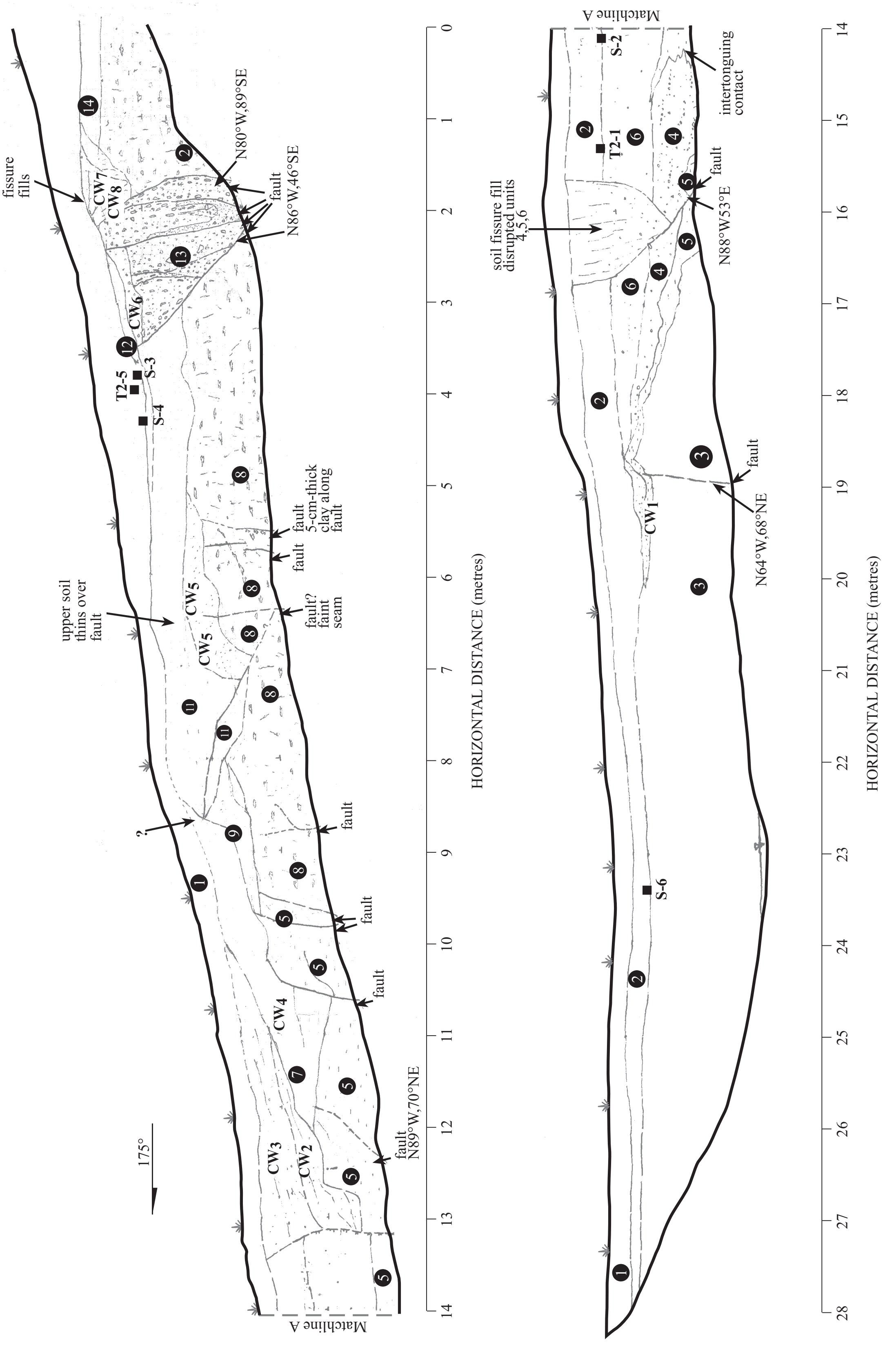


Figure 10. Elmalık Fault Trench T-2. cw: colluvial wedge.

and, in some cases, may have been larger. The pre-1999 penultimate event occurred about 300 years ago. The recurrence time between surface-faulting events appears to range from 300 to 800 years, although this range is based on only a limited number of radiocarbon dates and is not well constrained. With a reasonable degree of confidence, we conclude that the minimum recurrence interval is 300 years for surface-faulting events on the Düzce Fault segment.

The Bakacak and Elmalık faults exhibit strong geomorphic evidence of Holocene fault activity. In addition, trenches document the presence of repeated Late Holocene surface faulting events. It is critical to determine what fault, or sequence of faults, might rupture across the right stepover between the eastern end of the Düzce Fault and the southern branch of the NAFS in the Bolu area during an earthquake. On the basis of both field evidence and palaeoseismic data, we conclude that the Bakacak and Elmalık faults may rupture in one or both of two scenarios:

(1) *Sympathetic Rupture during Large Magnitude Earthquakes on the Main Southern Branch of the North Anatolian Fault System* – The segmented, possibly discontinuous nature of the Bakacak and Elmalık faults implies that these faults may not be mature, through-going Quaternary faults. This observation suggests that both the Bakacak and Elmalık faults are not likely to be independent seismic sources capable of generating large magnitude, large-slip earthquakes and also suggests that the stepover area (i.e., Bakacak/Elmalık faults) has not been the nucleation point in the past for a large earthquake with bilateral rupture onto the Düzce Fault and the southern strand of the NAFS. Rather, the Bakacak and Elmalık faults appear to be either relatively small faults capable of producing moderate-size earthquakes or faults that rupture sympathetic with large earthquakes on the bordering Düzce Fault and the southern strand of the NAFS. The western part of the Bakacak Fault ruptured during the 1999 Düzce earthquake. Rupture data from the 1944 event is not well documented, thus, it is not clear whether the Elmalık Fault ruptured during the 1944 earthquake (M=7.4). Interviews with residents and examination of cultural features along the Elmalık Fault did not identify any primary or secondary fault rupture along the fault. The 1944 earthquake occurred in February when thick snow covered the region and any surface rupture may have been concealed. However, Barka (1996) noted that rupture during the 1944 earthquake apparently decreased from about 3.5 m near Bolu, to 1.9 m or less near Abant Lake. Thus, it is possible that some coseismic slip may have occurred along the Elmalık and Bakacak faults.

(2) *Primary Rupture during Moderate Magnitude Earthquakes on the Fault Itself Producing Oblique Normal Surface Slip* – Palaeoseismic trench data show that the Bakacak and Elmalık faults have produced distinct surface faulting earthquakes during the Holocene (Figures 8–10). The recurrence interval between earthquakes on these faults appears to be much longer than the average repeat time for earthquakes on the main NAFS, although the repeat time is not well constrained by our trench data. Thus, the Bakacak and/or Elmalık faults may rupture as short, independent segments within the NAFS.

In conclusion, the Düzce Fault and the southern branch of the NAFS are separated by a 10- to 15-km-wide right stepover. Palaeoseismic trench data show that there have been four, and possibly five, surface-faulting events along the Düzce Fault in the past 2100 years. The most recent (or penultimate) event prior to the 1999 earthquake occurred about 300 years ago. The long-term recurrence interval ranges from 300 years to a maximum of 800 years or less. From palaeoseismic trenching, we conclude that the Düzce Fault typically ruptures in large magnitude earthquakes with surface rupture of 1 m or more. Past surface faulting events are generally of similar size, style, and location as the 1999 event.

Slip appears to be transferred across the stepover, in part, by Holocene activity on short intervening faults. These faults include the Bakacak and Elmalık faults. The Bakacak and Elmalık faults are geomorphically well expressed in the landscape, and palaeoseismic trench data indicate that they are active. These two faults form an obvious right-stepping structural connection between the Düzce Fault and the southern branch of the NAFS. In addition, slip transferred to these faults would be expressed in a releasing sense, consistent with extensional deformation and subsidence of Bolu Valley.

Acknowledgement

Radiocarbon analyses were performed by Dr. Gordon Seitz at the Lawrence Livermore laboratory. We thank ASTALDI and Yüksel-Rendal for providing facilities and support during field work.

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Received 09 July 2002; revised typescript accepted 05 February 2003