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Surface Rupture and Slip Distribution along the Karadere Segment of the 17 August 1999 İzmit and the Western Section of the 12 November 1999 Düzce, Turkey, Earthquakes

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Abstract On 17 August 1999 the M_w 7.5 İzmit, Turkey, earthquake produced surface rupture in excess of 120 km, and perhaps as much as 200 km, with up to 5 m of dextral slip, along a western portion of the North Anatolian fault zone. The 12 November 1999 M_w 7.1 Düzce, Turkey, earthquake produced a 40-km-long surface rupture, including 9 km of rupture overlap with the eastern end of the August event. Our mapping focused on the 40-km-long Karadere rupture segment, the easternmost segment of the August event, as well as on the western 20 km of the November rupture. Maximum dextral slip along the Karadere segment is approximately 1.5 m, and the average slip on this segment is close to 1 m. Although slip along the Karadere segment is considerably less than that on segments to the west, this segment is of particular interest for three reasons: (1) the western boundary of the Karadere segment is defined by the most striking structural discontinuity along the entire August surface rupture (i.e., a 5-km-wide zone of no surface rupture, as well as a 25° change in trend from E–W to ENE), and such a discontinuity may have important implications for rupture dynamics; (2) surface rupture terminates at the east end of the Karadere rupture segment at a 1.5- to 3-km-wide extensional step-over at Eften Lake; and (3) the 12 November 1999 Düzce earthquake reruptured the easternmost 9 km of the Karadere segment, raising interesting questions about rupture dynamics and interactions between events on adjacent fault segments. The details of the 17 August 1999 and 12 November 1999 surface rupture traces suggest that rupture may have partially propagated across the Eften Lake extensional step-over, although this step-over seems to have acted as an effective barrier to rupture propagation.

Introduction

On 17 August 1999 at 3:01 a.m. local time, a large earthquake (M_w 7.5, Reilinger *et al.,* 2000) occurred on one strand of the North Anatolian fault zone in western Turkey (Barka, 1999, Barka, *et al.,* 1999). The epicenter for this event is located about 10 km southeast of the city of İzmit. The 17 August 1999 İzmit earthquake continued the remarkable twentieth century sequence of westward-migrating events in which 11 events of M greater than or equal to 6.7 have ruptured almost the entire 1200-km-long North Anatolian fault system (Allen, 1969; Ambraseys, 1970; Barka, 1992). Stein *et al.*'s (1997) Coulomb failure stress modeling of the pre-1999 sequence suggested stress triggering of these events. The 12 November 1999 Düzce earthquake (M_w 7.1) reruptured the eastern 9 km of the August event (Hartleb *et al.,* 1999; Akyüz *et al.*, 2000, 2002). Vertical separations and dextral displacements measured after the November event greatly exceeded those of the August event at the same locations.

Detailed field mapping of the surface rupture trace indicates a minimum on-land rupture length of approximately 120 km for the 17 August 1999 event (Fig. 1; Barka, 1999; Barka *et al.*, 1999; Fumal *et al.*, 1999; R. D. Hartleb, unpublished data). Geodetic, seismological, and geologic data suggest that the rupture continued westward along offshore portions of the North Anatolian fault in the İzmit Bay, at least as far as Yalova, for a total rupture length exceeding 150 km, and perhaps as long as 200 km (Gülen *et al.*, 1999; Reilinger *et al.*, 2000; Gülen *et al.*, 2002). The western terminus of the rupture is located somewhere beneath the Sea of Marmara, and the exact total rupture length remains un-

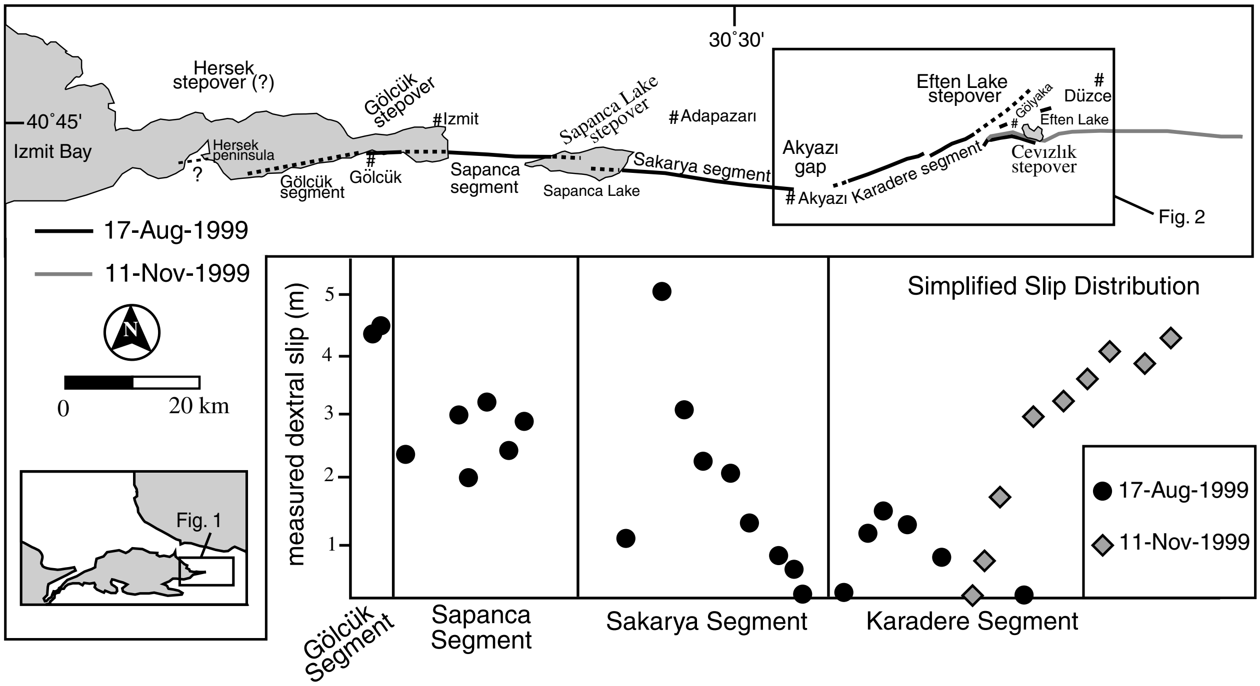

Figure 1. Simplified surface rupture map and slip distribution of the 17 August 1999 İzmit and 12 November 1999 Düzce, Turkey, earthquakes. The fault rupture trace has been dashed, where inferred. (Barka, 1999; Barka *et al.*, 1999; Fumal *et al.*, 1999; R. D. Hartleb, unpublished data).

known. Surface slip was observed to be almost pure right-lateral strike slip, and a maximum observed slip of about 5 m was measured near the town of Arifiye, about 10 km east of Sapanca Lake (Fig. 1). Vertical components of displacement, most notably normal faulting in the Gölcük and Eften Lake areas, are related to local fault geometry. Mapping teams identified four distinct rupture segments. The boundaries of these segments are coincident with fault stepovers, changes in strike, and/or other geometric complexities (Barka, 1999; Barka *et al.*, 1999; Fumal *et al.*, 1999; Langridge *et al.*, 2002). The rupture segments are, from west to east, the Gölcük, Sapanca, Sakarya, and Karadere segments (Fig. 1).

On 12 November 1999, another large earthquake (M_w 7.1) occurred in western Turkey (Akyüz *et al.*, 2000). The epicenter for this event is located near the city of Düzce. Detailed field mapping of the surface rupture trace of the 12 November l999 event indicates a total rupture length of approximately 40 km (Akyüz *et al.*, 2000), including approximately 9 km of overlap with the eastern end of the August rupture. The November surface trace is characterized by a predominance of dextral strike slip, with local components of normal and reverse displacements caused by local changes in the fault geometry. Maximum dextral slip of 5.00 $\pm$ 0.30 m was measured at the village of Güven, east of the area covered by this study. Average offset was closer to 3.00 m. In this article, we examine surface slip distribution and details of the rupture on the easternmost, 40-km-long Karadere segment of the l7 August 1999 rupture, as well as on the western 20 km of the 12 November 1999 rupture.

17 August 1999 Event Field Observations

Mapping of the l7 August 1999 rupture was performed between 17 August and 9 September l999 by an international team of scientists from Istanbul Technical University (ITU) (Istanbul, Turkey), the Southern California Earthquake Center (SCEC) (Los Angeles, California), the United States Geological Survey (Menlo Park, California), Osmangazi University (Eskişehir, Turkey), and the Institute de Physique du Globe (Paris, France). Mapping efforts were coordinated by Professor Aykut Barka (ITU). We present in this section a brief description of the 17 August 1999 surface rupture along the western three segments, followed by a more detailed treatment of slip distribution and surface rupture on the easternmost Karadere rupture segment.

Mapping of both the August and November events was carried out on 1:25,000 scale topographic maps and was aided by handheld global positioning system (GPS) receivers. Surficial slip measurements are based on the offset of cultural features, such as fencelines, roads, curbs, canals, tree lines, crop lines, and field boundaries. Most slip measurements were collected with a tape measure and therefore reflect near-field deformation (within ~5 m of the fault trace) only. At each site we measured the orientations of the fault and the offset feature, and we estimated the width of the fault zone. We also estimated the error associated with our slip measurements. Our error estimates were designed to encompass the full range of potential errors, including those associated with any irregularities in the measured feature, as well as those associated with the measurement itself. Detailed maps were made of a few selected sites with a portable electro-optical distance meter and electronic compass.

Surface Rupture West of the Karadere Segment

The approximately N70°E-trending Gölcük rupture segment extends from the point at which surface rupture trends offshore at Değirmendere, just east of the city of Gölcük, to the eastern end of the Sea of Marmara. Maximum dextral displacement on this segment was 4.55 ± 0.15 m at the Naval base in Gölcük (Fig. 1; Barka *et al.*, 1999; R. D. Hartleb, unpublished data). The total onshore length of this segment of 12 km is almost certainly a minimum for the segment as a whole because the sea wall where faulting trends offshore to the west is offset right laterally by about 4 m. Also note that along this segment are the approximately 2-m-high, down-to-the-north normal fault scarps near the city of Gölcük. These accommodate a local, few-kilometers-wide extensional bend in the fault. Unlike several of the fault step-overs discussed subsequently, surface rupture across this extensional bend was continuous.

The N82–90°E-trending Sapanca segment extends for 15 km from the eastern end of the Sea of Marmara to Lake Sapanca. Maximum dextral displacement on this segment is approximately 3.5 m (Fig. 1). The Sapanca segment is characterized by a relatively simple, narrow (1–5 m wide), straight fault trace. The eastern terminus of this segment coincides with a 1- to 2-km-wide extensional step-over beneath Lake Sapanca (Fig. 1).

The N85°E-trending Sakarya segment extends for 30 km from the Lake Sapanca extensional step-over in the west to the town of Akyazı and another extensional step-over in the east. Detailed field observations from most of the length of this rupture segment are presented in Langridge *et al.* (2002). The greatest displacements from the August event are observed along this segment. Surface rupture is typically expressed as a narrow (2–8 m wide) fault zone, with right-lateral strike-slip displacements ranging from less than 1 m to a maximum of 5.1 ± 0.25 m near the town of Arifiye (Fumal *et al.*, 1999). The Sakarya segment is characterized by a series of several-kilometer-long sections separated by narrow (hundreds of meters wide) extensional step-overs and at least one minor compressional step-over (Fig. 1).

We mapped the easternmost 3 km of the Sakarya segment, east of the section mapped by Fumal *et al.* (1999). Slip on the easternmost Sakarya segment diminishes markedly eastward, from the more than 5 m of slip measured by Fumal *et al.* (1999) near the center of the segment to zero at a point 1 km east of the town of Akyazı (Fig. 1). We mapped two 100-m-wide extensional steps on the Sakarya segment just northwest of the town of Akyazı. As slip gradually decreases to zero eastward from Akyazı, the surface expression of faulting widens into a 400-m-wide zone of distributed surface cracking; individual cracks have displacement ranging from zero to a few centimeters. Despite an intensive search for a continuation of surface rupture, a 5-km-wide gap with no discernible surface rupture separates the eastern terminus of the Sakarya segment from the western edge of the Karadere segment.

Karadere Segment

The 40-km-long Karadere rupture segment is the easternmost segment of the 17 August 1999 rupture and extends from 5 km east of the town of Akyazı to the town of Cevızlık, south of Eften Lake (Figs. 1 and 2). Our mapping efforts were concentrated here, and we collected approximately 40 slip measurements along this segment (Fig. 3 and Table 1). A maximum dextral slip of 1.55 ± 0.10 m was recorded along this segment at a site located 6 km west of the town of Gölyaka. At this location, the fault trends N50°E, and the measurement was made on a wooden-post, barbed-wire fence oriented at N55°W. The fault zone at this location is approximately 1–1.5 m wide. Average surface slip on the Karadere segment as a whole is close to 1 m.

Although the slip along the Karadere segment is considerably less than those on the segments to the west, this segment is of particular interest for three reasons: (1) the western boundary of the Karadere segment is defined by the most striking structural discontinuity along the entire l7 August 1999 surface rupture (the Akyazı surface-rupture gap), (2) the 17 August 1999 rupture terminated along this segment near the Eften Lake step-over, raising the question “why there?”, and (3) the l2 November 1999 event reruptured the easternmost 9 km of this segment, raising interesting questions about the rupture dynamics and the interactions between the events on adjacent fault segments.

The Karadere segment appears to be quite different from the three segments to its west. Average slip along the Karadere segment is about l m, whereas average slip for the other three segments is 2.5–4 m. In addition to the lower average slip along the Karadere segment, the Karadere segment trends ENE, approximately 25° off the strike of the rest of the E–W-trending rupture. Finally, between the eastern terminus of the Sakarya segment and the western terminus of the Karadere segment, there is a 5-km-wide zone of no surface rupture. Clearly the Akyazı surface-rupture gap represents some sort of structural discontinuity, and such a discontinuity may have important implications for rupture dynamics.

The westernmost section of the Karadere rupture segment, east of the town of Akyazı, comprises a wide (~400 m) zone of distributed cracking. Individual cracks have zero to a few centimeters of displacement. This zone of cracking gradually coalesces eastward into a discrete, narrow (1–5 m wide) fault zone just west of the town of Çariğikuru, where dextral offsets range from 0.55 (+10/−15) to 1.15 (±15) m. Between the towns of Haraklı and Karadere the surface rupture is relatively straight and simple. The faulting trends

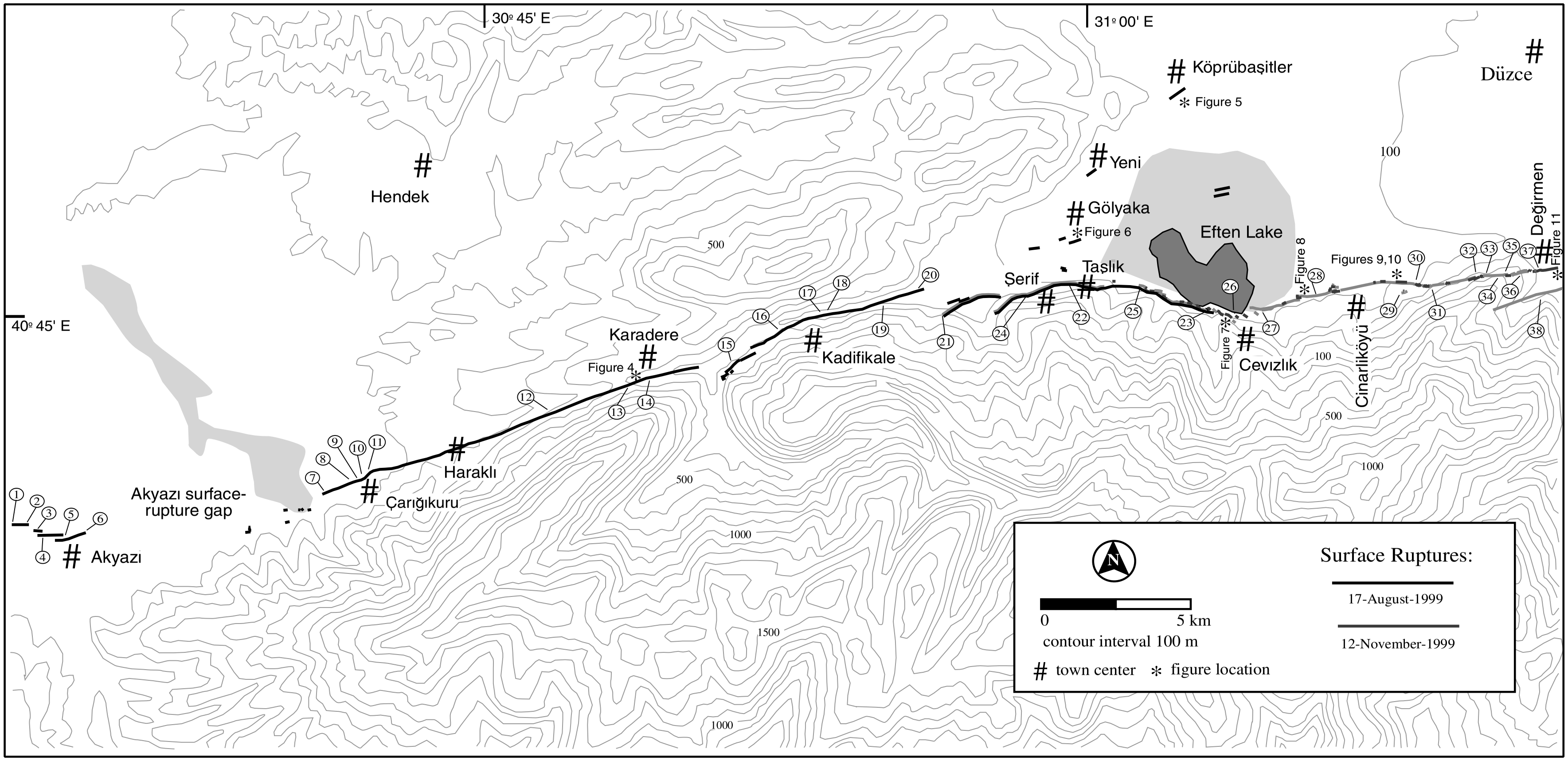

Figure 2. Detailed rupture map of the Karadere rupture segment of the 17 August 1999 İzmit earthquake and the western section of the 12 November 1999 Düzce earthquake. Circled numbers correspond to locations detailed in Table 1. Pale gray shading denotes marshy areas.

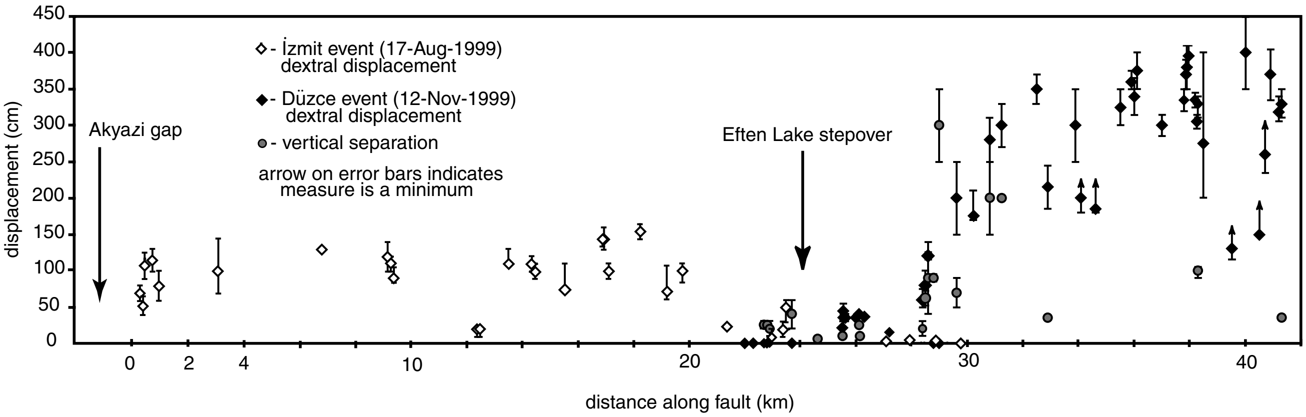

Figure 3. Slip distribution of the Karadere rupture segment of the 17 August 1999 İzmit earthquake and the western section of the 12 November 1999 Düzce earthquake.

N65°E for 10 km along this reach and is restricted to a 1- to 3-m-wide zone. Right-lateral slip varies between 0.90 (+0.15/−0.05) and 1.30 (±0.05) m (Fig. 4). Four kilometers east of the town of Kadifekale, there is a 400-m-wide compressional step-over or bend (Fig. 2). Within a few hundred meters to the east and west of this compressional step or bend, faulting is distributed throughout a wide zone of surface cracking, each crack having less than a few centimeters of displacement.

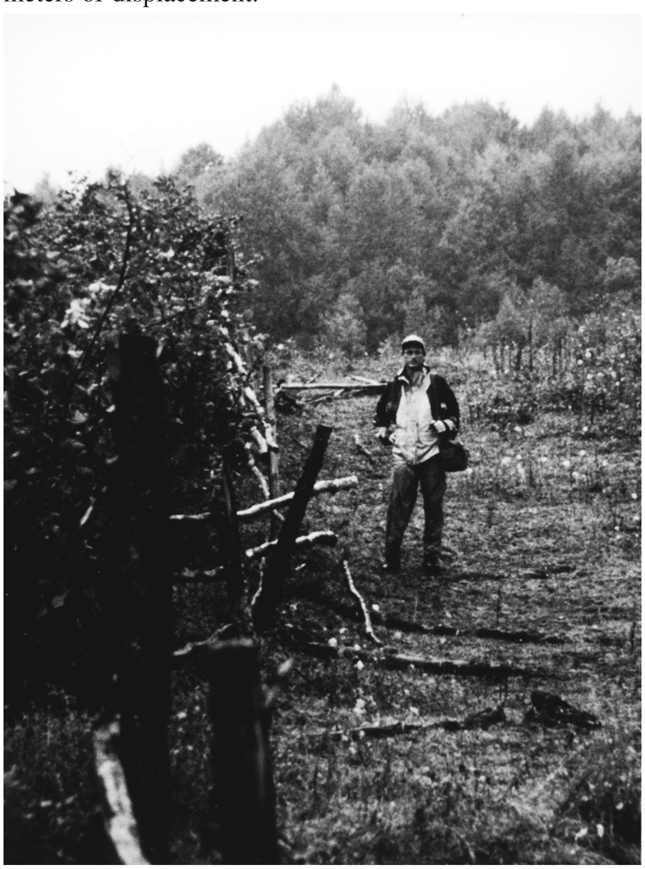

Figure 4. Photograph of offset fenceline (1.20 ± 0.20 m dextral) near the town of Karadere, 17 August 1999 event. View south. See Figure 2 for location.

Between the Kadifekale and the Gölyaka valley, surface rupture closely follows an east-flowing drainage, crossing this drainage many times. In places, the surface rupture is completely obscured by the active drainage. The fault zone in this region was measured to be 1.5–3 m wide, but because of the paucity of cultural features in this area, combined with the low angle between surface faulting and the channel margin, estimation of total slip in this region was difficult.

As the surface rupture trace enters the alluvial valley surrounding the town of Gölyaka, faulting becomes discontinuous and less discrete. Though the geomorphology sug-

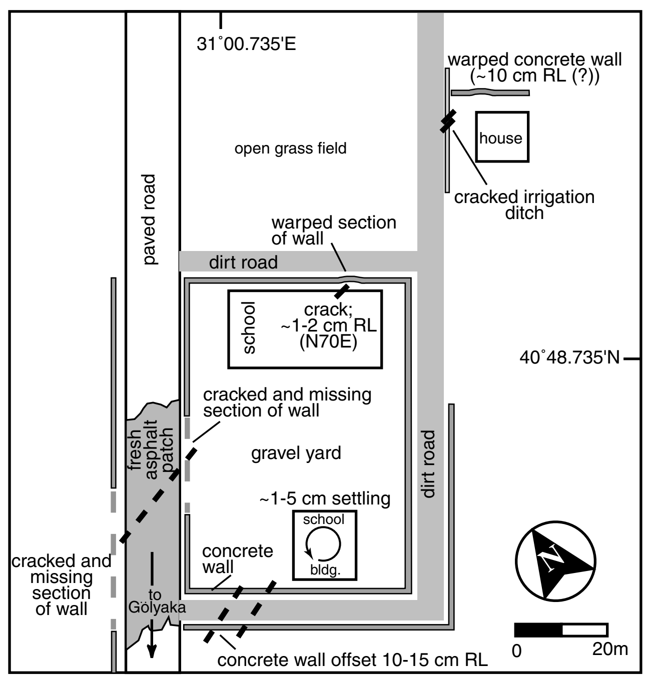

Figure 5. Sketch map of the Köprübaşitler (Içmeler) school site, showing northeastern terminus of the 17 August 1999 İzmit earthquake surface rupture. Surface faulting and cracking shown in heavy black lines. See Figure 2 for location.

Table 1
Selected Displacement Measurements from the Karadere Segment of the 17 August 1999 İzmit and the Westernmost Section of the 12 November 1999 Düzce, Turkey, Earthquakes. Locations Keyed to Figure 2

Site (see Fig. 2)	Dextral Displacement (cm)	Vertical Displacement (cm)*	Fault Strike (local)	Strike of Offset Feature	Offset Feature and Remarks
The 17 August 1999 İzmit event					
1	45 ± 5	–	~N90E	~N0E	Tree line and road edge
2	30 ± 10	–	~N82W	~N20E	Concrete wall
3	48 ± 10	–	N65-75E	N3E	Concrete wall
4	20(−5/+10)	–	N75-80E	~N15E	Concrete wall, fault zone ~15 m wide
5	14 ± 6	–	N80W	N0E	Concrete sidewalk
6	1–2	–	N65-70E	N5W	Concrete swimming pool, fault zone ~25 m wide
7	15 ± 5	–	N40-90E	–	In the broad zone of cracking
8	70 ± 10	–	N72-80E	N21W	Wooden fence posts
9	115(+10/−25)	–	~N65E	~N20W	Cart path wheel ruts
10	115 ± 15	–	N64E	N11W	Concrete fence posts; fault zone ~7 m wide
11	80 ± 20	–	N42E	N15W	Wooden fence posts
12	130 ± 5	–	N77-78E	N15W	Concrete fence posts
13	120 ± 20	15–30 (N)	N77E	N20W	Wooden fence posts
14	110 ± 10	–	N76-80E	N20-25W	Concrete fence posts
15	~20	–	N30-40E	–	In broad zone of cracking
16	100 ± 10	–	N54E	N35W	Wooden fence posts
17	145(+20/−10)	–	N60-70E	~N10E	Road edge
18	145 ± 15	–	N55E	N27W	Wooden fence posts
19	155 ± 10	–	N50E	N55W	Wooden fence posts
20	100(+10/−15)	–	N72E	~N20W	Tree line and road edge, fault zone ~20 m wide
21	1–5	–	~N45E	–	Ground cracking
22	50(+10/−20)	–	N65E	N13W	Wooden fence posts
23	0–5	–	N70W	–	Easternmost surface cracking
The 12 November 1999 Düzce event					
24	~12	~5 (N)	N75E	~N90E	Fence line
25	80 ± 20	62 ± 10 (N)	N82W	N2E	Drainage ditch
26	270 ± 30	2(+50/−30) (N)	N50W	N6E	Wooden pier
27	340(+30/−40)	50? (N)	N60-65E	N15W	Stone wall
28	190(+10/−20)	–	N90E	N20W	Wooden fence posts
29	~15	–	N45E (?)	–	Ground cracking
30	380 ± 30	–	N80-85E	N20-30W	Wooden fence posts, wheel ruts, and ditch
31	330 ± 10	100 (S)	N74E	N22W	Concrete fence posts
32	130 ± 15	4 (S)	N69E	N14W	Wooden fence posts
33	400 ± 50	–	N90E	N15W	Wooden fence posts
34	250(+10/−20)	40–65 N	N82E	N12W	Irrigation ditch, minimum estimate
35	370 ± 35	–	N72E	N10E	Stone wall and wheel rut
36	330(+10/−25)	–	N73E	N20W	Offset river bank (cobble gravel)
37	330 ± 20	35 (S)	N86E	N30W	Wooden fence posts and road edge
38	~15		N72E	–	Ground cracking

*(N) indicates down-to-the-north normal displacement, (S) indicates down-to-the-south normal displacement.

gests that a mountain-front fault strand may be present along the northern edge of the valley, no continuous surface rupture was observed there. Isolated ground cracking and rotational deformation were noted ca. 2 km north of Gölyaka at the center of the small town of Yeni (Fig. 2). There is minor ground cracking at this location, as well as a warped concrete wall that displays less than 10 cm of dextral displacement. The mosque in the center of the town of Yeni has been rotated by approximately 3°–5° in a clockwise direction. The northeastern extent of surface rupture appears to be located in the town of Köprübaşkurtler (Içmeler) (Fig. 5). At this location, we mapped a series of ground cracks, each with dextral displacement less than a few centimeters, as well as a number of warped and offset concrete walls and fences with dextral displacement up to 15 cm.

Additionally, diffuse ground cracking and rotational deformation were noted just south of the town of Gölyaka (Fig. 6). At this site, we mapped a 60-m-wide zone of discontinuous surface faulting and ground cracking. Dextral displacements on individual strands ranged from 0 to 12 cm, and two small strands, each having a sinistral displacement of about 2 cm, were observed. A 5-m-long, 2-m-wide graben with 30–50 cm of relief was mapped within this zone of faulting. Within and adjacent to this zone of faulting, we also noted at least four buildings that had experienced clockwise rotation between 5° and 12°. Two buildings experi-

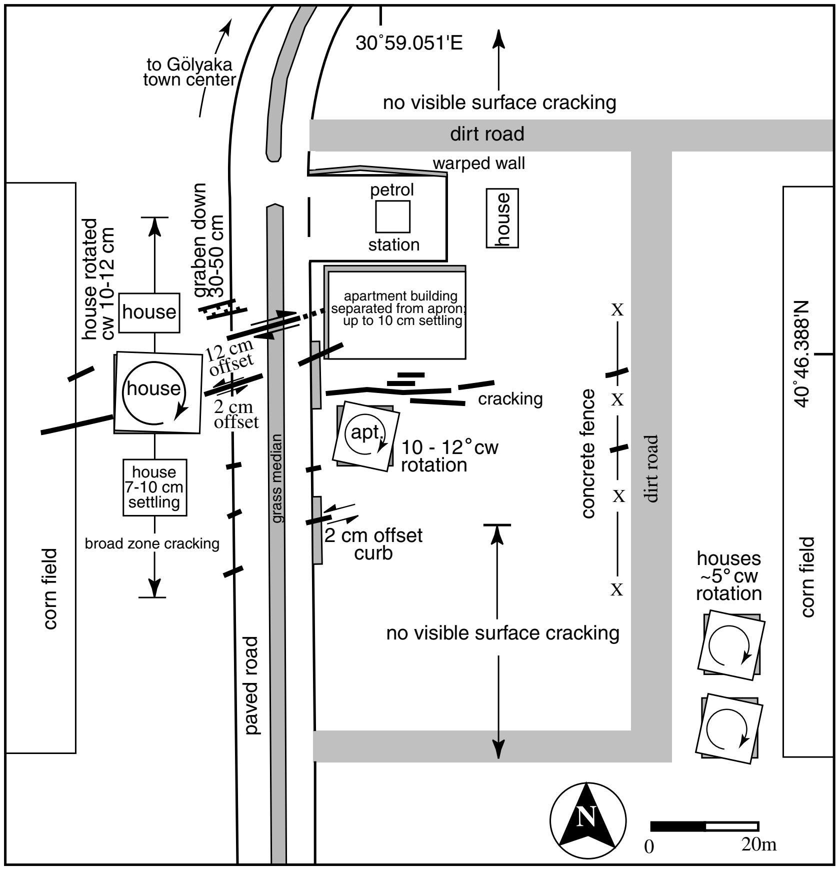

Figure 6. Sketch map of broad zone of dextral shear and clockwise rotation at Gölyaka, 17 August 1999 İzmit earthquake. Surface faulting and cracking shown in heavy black lines. See Figure 2 for location.

enced significant settling, perhaps as much as 7–10 cm. Local residents reported that this settling seemingly increased with time for up to a week after the l7 August 1999 event.

Another broad zone of cracking was noted about 1 km north of Eften Lake. At least 70 distinct cracks were recognized here, within a 420-m-wide zone. Most of the cracks trend N60–70°E, and have no evident displacement, though some individual cracks have up to 3–4 cm of dextral displacement, 1–2 cm of vertical separation, and 1–2 cm of opening. These cracks were best developed where they crossed a hard-packed dirt road, but many of them also extended at least tens of meters into the fields on either side of the road.

Following the 17 August 1999 event, discontinuous ground cracking was evident along the mountain front at the southern edge of the alluvial valley surrounding Gölyaka. Maximum dextral displacements along the southern mountain front of $0.50(+0.10/-0.20)$ m were observed at the town of Taşlık (Figs. 2 and 3). Displacements gradually decrease to zero along the southern mountain front to the east and west from this point. The southeastern terminus of the 17 August 1999 rupture is located in the town of Cevızlık, at the southeast end of Eften Lake.

The 12 November 1999 Event—Field Observations

Mapping of the western third of the 12 November 1999 event was conducted between 15 November and 23 November 1999 by Hartleb (SCEC), Toraman (ITU), and Çakir (ITU). The 12 November 1999 Düzce earthquake ruptured a 40-km-long section of the Düzce fault, a splay of the North Anatolian fault (Fig. 1). The November event was initiated in an area of elevated Coulomb failure stress following the August event (Hubert-Ferrari, 1999; U.S. Geological Survey, 2000). The Düzce earthquake reruptured approximately 9 km of the Karadere segment of the 17 August 1999 İzmit event along the southern mountain front (Fig. 2). The November displacements, however, were much greater than those observed just 3 months earlier following the August event (Fig. 3 and Table 1). Dextral slip exceeding 3 m and down-to-the-north normal scarps exceeding 2.5 m in height were observed in the town of Cevızlık after the November event. No rerupturing of the section of the Karadere segment along the northern mountain front was noted following the November event.

Displacements measured from the western extent of the November rupture to a point approximately 5 km west of

Figure 7. Photograph of the offset pier (2.70 ± 0.50 m dextral, 2.00 ± 0.25 m down-to-the-north) located on the southern edge of Eften Lake, 12 November 1999 event. View north. See Figure 2 for location.

Cevızlık did not exceed 50 cm, and in places the surface rupture trace was manifested by surface cracking with little or no apparent offset. Offsets increase markedly to the east of this location, with a dextral displacement of 0.80 ± 0.20 m and 0.60 ± 0.10 m of down-to-the-north separation at a point 3.5 km west of Cevızlık, and down-to-the-north normal scarps exceeding 3 m in height at a point 3 km east of Cevızlık. A 250-m-wide extensional step at the town of Cevızlık, south of Eften Lake, is accommodated by a series of en-echelon, northwest-trending, down-to-the-north normal scarps with up to 3.5 m of vertical separation and dextral displacements in excess of 2.5 m (Fig. 7). Liquefaction features, including extrusive gray sands, were visible under the waters of Eften Lake for a short time following the earthquake, and local residents report emission of a flammable gas (probably methane) from a few point sources within the town of Cevızlık. There is an abrupt transition to almost pure strike slip just east of Eften Lake, with dextral displacements on the order of 2–3.5 m (Fig. 3).

A detailed instrumental survey of an offset fence located 1.5 km west of the town of Çinarliköyü (in the town of Yeni) was conducted in August 2000 (Fig. 2). At this location a wooden-post, barbed-wire fence at a high angle to the surface rupture was surveyed for approximately 35 m north and south of the fault (Fig. 9). The fault zone at this location is about 2.5 m wide, and the fence is remarkably straight, with no evidence of any distributed slip outside of the narrow fault zone. The survey map shows 1.85–2.10 m of dextral displacement, an amount that is in good agreement with the 1.75–2.00 m of displacement estimated in November 1999 by the traditional method using a tape measure. This finding does not obviate the conclusions of Rockwell *et al.* (2002) but merely suggests that in some cases all or nearly all of the surface slip can, in fact, be accommodated in a narrow (few meters wide) zone.

Another detailed instrumental survey was conducted in August 2000 in the town of Çinarliköyü. At this location, a straight concrete wall at a high angle to the rupture trace extends more than 25 m north and 12 m south of faulting (Figs. 9 and 10). The main fault zone is 1.5–2.5 m wide, with a discontinuous secondary strand 2–3 m to the north. This survey shows 3.60–4.50 m of dextral offset on the two strands, a number that is somewhat larger than the 3.50–3.70 m estimated on 19 November 2000 by the traditional method of using a tape measure. Part of this discrepancy is caused by the difficulties associated with eyeballing the concrete wall across the fault zone, as well as the uncertainty associated with local strike of the fault zone. Though it is less clear here than at the Yeniköy offset fence site, there does not appear to be significant off-fault distributed deformation at Çinarliköyü. Indeed, the tape measure estimate of offset is less than that determined from the survey, but the survey

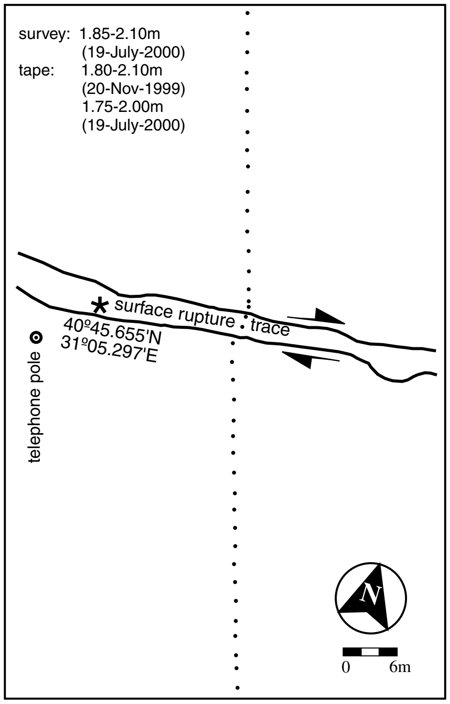

Figure 8. Instrumental survey map of the offset wooden-post, barbed-wire fence at Yeni village. Asterisk marks survey shot point, with GPS-derived latitude and longitude. Estimates of offset derived from tape and compass method and instrumental survey as noted. See text for details, see Figure 2 for location.

shows the concrete wall to be remarkably straight on either side of the faulting. This discrepancy is thought to be primarily the result of human error during our initial field mapping.

A 12-m-diameter, up to 50-cm-high deposit of extruded fine- to medium-grained gray sand was noted in the town of Çinarliköyü. This sand blow deposit appeared to have been extruded directly from the main rupture trace and was located at a point where faulting crossed a 1-m-wide irrigation canal. It is believed that locally saturated conditions in the near surface contributed to the formation of this extrusive deposit. Similar features were also seen about 2.5 km farther to the east.

Surface rupture between Çinarliköyü and Değirmen is predominantly pure dextral strike slip with displacements ranging from 2.5 to 4.5 m. A small (<100 m wide) extensional step located 2.5 km east of Cinarliköyü is accommodated by a series of en-echelon, northwest-trending normal faults. South of the town of Değirmen, there is a 1.5-km-long fault strand parallel to, and 1 km south of, the main rupture trace. Displacements on this southern strand do not exceed 0.15 m. The eastern channel margin of the Develisuyu River (at the eastern edge of our study area) is offset dextrally to the extent of 3.30 ± 0.20 m, and the western channel margin is offset dextrally by 3.30(+10/−0.25) m (Fig. 11).

Discussion

Figure 3 shows the slip distribution data for the Karadere segment of the 17 August 1999 İzmit earthquake and the slip measurements for the western half of the 12 November 1999 Düzce earthquake. For the August event, this distribution is fairly smooth and regular, with a maximum dextral slip of 1.5 ± 0.10 m and an average of about 1 m. Estimated surface slip near and within the diffuse zones of cracking associated with the Akyazı surface rupture gap and the Eften Lake step-over is relatively low, in part because the methods we used to estimate slip (tape measure and compass) are best suited to measuring narrow, near-field zones of deformation. The observation of the ends of the rupture segments, as mapped after the 17 August 1999 event, suggests the generality that surface rupture patterns tend to splay from a narrow, discrete fault zone into a broad, horsetail pattern near step-overs. This may be a primary effect of rupture dynamics, or, alternatively, may represent a manifestation of differing surface rupture patterns in different near-surface materials. It is assumed that thicker unconsolidated sediment packages are associated with step-overs, and perhaps observed rupture patterns reflect differences in near-surface materials.

The Karadere rupture segment extends for 40 km from Akyazı to Cevızlık. Assuming a rupture width of 12 km, a near-vertical fault plane, and an average slip of 1 m for the segment, approximate moment release (M_0) from rupture on the Karadere segment is 1.5×10^{26} dyne cm, yielding a moment magnitude (M_w) of 6.7 for this segment.

Although the eastern end of the 17 August 1999 surface rupture is spatially associated in a general sense with what appears to be a 1- to 3-km-wide right (extensional) step in the fault zone (near Eften Lake), the details of the surface rupture trace suggest that the rupture may have at least partially propagated across this step before rupture termination. Continuous ground cracking was mapped for 9 km along the mountain front south of Eften Lake after the August event, with 0–0.5 m of displacement (Figs. 2 and 3, Table 1). The August displacements measured on the mountain front south of Eften Lake are much less than those on the northern mountain front, northwest of Eften Lake (Figs. 2 and 3, Table 1), but are consistently right lateral and associated with a mole track pattern of rupture. If the August rupture did indeed jump the Eften Lake step-over, it remains unclear as to what caused the termination of the rupture at its eastern end. One possibility, however, is suggested by the surface rupture pattern of both the 17 August and 12 November 1999 events. There is a narrow (∼250 m wide) extensional step centered at the town of Cevızlık (Fig. 2). No ground cracking was mapped east of Cevızlık following the 17 August l999 event, yet mapping of this area following the 12 November l999 event shows en-echelon, northwest-trending normal faults. Perhaps the August rupture just managed to propagate across the Eften Lake step-over but was arrested by the smaller step-over at Cevızlık.

Figure 9. Photograph of the offset concrete wall in the town of Çinarliköyü, 12 November 1999 event. View south. See Figure 2 for location and Figure 10 for instrumental survey map.

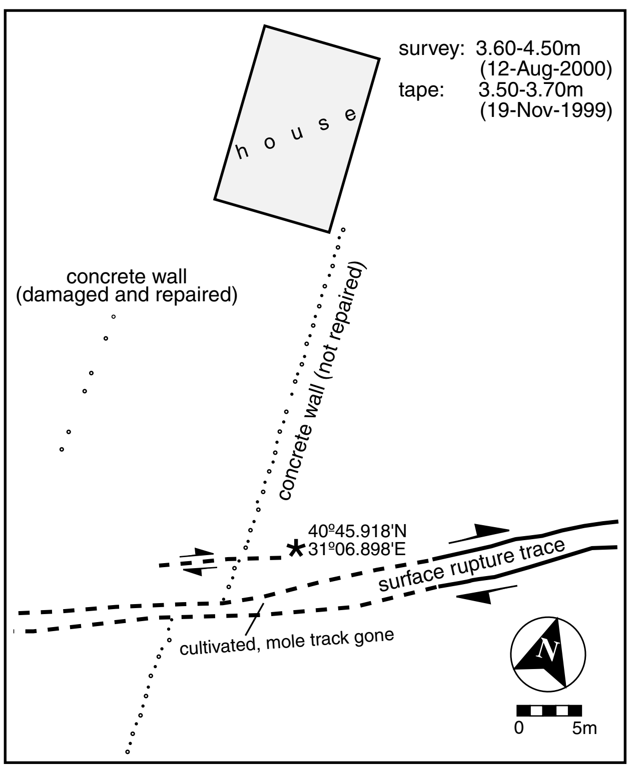

Figure 10. Instrumental survey map of the offset concrete wall at Çinarliköyü. Asterisk marks survey shot point, with GPS-derived latitude and longitude. Estimates of offset derived from tape and compass method and instrumental survey as noted. The surface rupture trace has been dashed, where inferred. See text for details, see Figure 2 for location.

It is possible that the Eften Lake step-over did in fact terminate the 17 August 1999 rupture and that cracking east of this step-over is a manifestation of dynamic overshoot or triggered afterslip. A number of local residents in and around Gölyaka were interviewed in an attempt to ascertain the relative timing of surface rupturing in this area. Unfortunately, however, it is not known whether a time delay accompanied the transfer of slip across the Eften Lake step-over from the strand along the northern mountain front to that along the southern mountain front. The mainshock occurred at approximately 3:01 a.m. local time, and local residents did not closely examine the rupture until a few hours later at daybreak. It is apparent, however, from the accounts of eyewitnesses that surface rupture south of the Eften Lake step-over occurred coincidentally with, or within just a few hours after, surface rupture north of the step-over.

Conclusions

Detailed surface rupture mapping, including displacement measurements, of the Karadere segment of the l7 August 1999 İzmit and the westernmost section of the 12 November 1999 Düzce, Turkey, earthquakes of the western North Anatolian fault zone was conducted shortly after each event. This mapping shows the Karadere segment of the 17 August rupture to be exceptional with respect to the other rupture segments. The Karadere segment is characterized by lower average displacement, strikes 25° off from the other rupture segments, and is bounded on the east and on the west

Figure 11. Photograph of the Develisuyu River offset channel margin (3.30[+0.10/−0.35] m dextral), 12 November 1999 event. View north. See Figure 2 for location.

by major structural discontinuities. To the west of the Karadere segment is the 5-km-wide Akyazı surface rupture gap, to the east is the 1- to 3-km-wide Eften Lake step-over. The Eften Lake step-over is clearly associated with the arrest of the August event and the initiation of the November event, but the details of this are not yet well understood. The 12 November 1999 event reruptured the eastern 9 km of the 17 August 1999 surface rupture, with a much larger right-lateral offset and a large component of the north-side-down normal displacement.

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References

Akyüz, H. S., A. Barka, E. Altunel, R. Hartleb, and G. Sunal (2000). Field observations and slip distribution of the November 12, 1999 Düzce earthquake ($M = 7.1$), Bolu, Turkey, in *The 1999 İzmit and Düzce Earthquakes: Preliminary Results,* A. Barka, Ö. Kozacı, S. Akyüz, and E. Altunel (Editors), Istanbul Technical University Publication, Istanbul, 63–70.

Akyüz, H. S., R. Hartleb, A. Barka, E. Altunel, G. Sunal, B. Meyer, and R. Armijo (2002). Surface rupture and slip distribution of the 12 November 1999 Düzce Earthquake (M 7.1), North Anatolian Fault, Bolu, Turkey, *Bull. Seism. Soc. Am.* **92,** no. 1, 61–66.

Allen, C. R. (1969). Active faulting in northern Turkey, Contribution Number 1577, Division of Geological Sciences, California Institute of Technology, 32 pp.

Ambraseys, N. N. (1970). Some characteristic features of the Anatolian fault zone, *Tectonophysics* **9,** 143–165.

Barka, A. A. (1992). The North Anatolian fault zone (supplement), *Ann. Tectonicae* **6,** 164–195.

Barka, A. A. (1999). The 17 August 1999 İzmit earthquake, *Science* **285,** 1858–1859.

Barka, A. A., S. Akyüz, E. Altunel, G. Sunal, Z. Çakir, A. Dikbaş, B. Yerli, T. Rockwell, J. Dolan, T. Dawson, R. Hartleb, A. Tucker, T. Fumal, R. Langridge, H. Stenner, S. Christofferson, R. Armijo, B. Meyer, and J. Chabalier (1999). 17 August 1999 İzmit, Turkey earthquake, northwestern Turkey (abstract), *EOS* **33,** F-647.

Fumal, T., R. M. Langridge, H. Stenner, S. Christofferson, J. Dolan, R. Hartleb, T. Rockwell, T. Dawson, A. Tucker, Z. Çakir, A. Dikbaş, B. Yerli, and A. Barka (1999). Slip distribution and geometry of the Sakarya section of the 1999 İzmit earthquake ground rupture, western Turkey (abstract), *EOS* **33,** F-669.

Gülen, L., D. Kalafat, A. Pinar, N. Özel, G. Horasan, and A. M. Işıkara (1999). Surface breaks of the August 17, 1999 İzmit (Kocaeli) Earthquake ($M_s = 7.8$) (abstract), *EOS* **33,** F-669.

Gülen, L., A. Pinar, D. Kalafat, N. Özel, G. Horason, M. Yılmazer, and A. M. Işıkara (2002). Surface fault breaks, aftershock distribution, and rupture process of the 17 August 1999 İzmit, Turkey, earthquake, *Bull. Seism. Soc. Am.* **92,** no. 1, 230–244.

Hartleb, R. D., T. J. Dawson, A. Z. Tucker, J. F. Dolan, T. K. Rockwell, B. Yerli, A. Dikbaş, Z. Çakir, T. Gürer, O. Uslu, and A. A. Barka (1999). Surface rupture and slip distribution along the Düzce strand of the l7 August 1999 İzmit, Turkey, Earthquake (abstract). *EOS* **33,** F-675.

Hubert-Ferrari, A., A. A. Barka, E. Jacques, S. S. Nalbant, B. Meyer, R. Armijo, P. Taponnier, and G. C. King (1999). Seismic hazard in the Marmara Sea region following the 17 August l999 İzmit earthquake, *Nature* **404,** 269–273.

Langridge, R. M., H. D. Stenner, T. E. Fumal, S. A. Christofferson, T. K. Rockwell, R. D. Hartleb, J. Bachhuber, and A. A. Barka (2002). Geometry, slip distribution, and kinematics of surface rupture on the Sakarya fault segment during the 17 August 1999 İzmit, Turkey, earthquake, *Bull. Seism. Soc. Am.* **92,** no. 1, 107–125.

Reilinger, R. E., S. Ergintav, R. Bürgmann, S. McClusky, O. Lenk, A. Barka, O. Gurkan, L. Hearn, K. L. Feigl, R. Cakmak, B. Aktug, H. Ozener, and M. N. Töksoz (2000). Coseismic and postseismic fault slip for the 17 August 1999, $M = 7.5$, İzmit, Turkey earthquake, *Science* **289,** 1519–1524.

Rockwell, T. K., S. Lindvall, T. Dawson, R. Langridge, and W. Lettis (2002). Lateral offsets on surveyed cultural features resulting from the 1999 İzmit and Düzce Earthquakes, Turkey, *Bull. Seism. Soc. Am.* **92,** no. 1, 79–94.

Stein, R. S., A. A. Barka, and J. H. Dietrich (1997). Progressive failure on the North Anatolian fault since 1939 by earthquake stress triggering, *Geophys. J. Int.* **128,** 594–604.

U.S. Geological Survey (2000). Implications for earthquake risk reduction in the United States from the Kocaeli, Turkey, earthquake of August 17, 1999, U.S. Geological Survey Circular 1193, 64 pp.

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