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The Surface Rupture and Slip Distribution of the 17 August 1999 İzmit Earthquake (*M* 7.4), North Anatolian Fault

by A. Barka, H. S. Akyüz, E. Altunel, G. Sunal, Z. Çakir, A. Dikbas, B. Yerli, R. Armijo, B. Meyer, J. B. de Chabalier, T. Rockwell, J. R. Dolan, R. Hartleb, T. Dawson, S. Christofferson, A. Tucker, T. Fumal, R. Langridge, H. Stenner, W. Lettis, J. Bachhuber, and W. Page

Abstract The 17 August 1999 İzmit earthquake occurred on the northern strand of the North Anatolian fault zone. The earthquake is associated with a 145-km-long surface rupture that extends from southwest of Düzce in the east to west of Hersek delta in the west. Detailed mapping of the surface rupture shows that it consists of five segments separated by releasing step-overs; herein named the Hersek, Karamürsel–Gölcük, İzmit–Sapanca Lake, Sapanca–Akyazi, and Karadere segments from west to east, respectively. The Hersek segment, which cuts the tip of a large delta plain in the western end of the rupture zone, has an orientation of N80°. The N70°–80°E–trending Karamürsel–Gölcük segment extends along the linear southern coasts of the İzmit Gulf between Karamürsel and Gölcük and produced the 470-cm maximum displacement in Gölcük. The northwest–southeast-striking Gölcük normal fault between the Karamürsel–Gölcük and İzmit–Sapanca segments has 2.3-m maximum vertical displacement. The maximum dextral offset along the İzmit–Sapanca Lake segment was measured to be about 3.5 m, and its trend varies between N80°E and east–west. The Sapanca–Akyazi segment trends N75°–85°W and expresses a maximum displacement of 5.2 m. The Karadere segment trends N65°E and produced up to 1.5-m maximum displacement. The Karadere and Sapanca–Akyazi segments form fan-shape or splaying ruptures near their eastern ends where the displacement also diminished.

Introduction

The 17 August 1999 İzmit earthquake (M_s 7.4) struck the eastern Marmara region at 03.02 a.m. (local time) and resulted in at least 18,000 deaths (official count), more than 25,000 injuries, and collapse or heavy damage of about 75,000 buildings in the cities of Adapazarı, İzmit, Yalova, İstanbul, and Bolu, all located within or adjacent to the rupture zone.

The 17 August 1999 earthquake was the seventh in a sequence of westward-migrating earthquakes along the North Anatolian fault (Fig. 1). The time interval between these earthquakes varied from 3 months to 32 yr, including the 1999 event. This earthquake sequence began in 1939 and caused rupture along a 1000-km section of the fault, with maximum horizontal displacements of up to 7.5 m. Figure 2 shows the slip distribution resulting from this migration including the 1951 and the 12 November 1999 earthquakes. The epicenter of the 17 August earthquake was located at 40.8° N latitude and 30° E longitude, and the earthquake had a depth of around 17 km (USGS). The maximum ground motion was measured as 0.45*g* (Erdik and Durukal, 2000). The earthquake lasted 45 sec (USGS) and consisted of several subevents (Pınar *et al.,* 2000; Gülen *et al.,* 2002). The nearest major cities affected by the earthquake were İzmit, Gölcük, Yalova, and Adapazari, all located near the eastern end of the Marmara Sea. The earthquake also caused considerable damage in İstanbul, in the district of Avcilar, located in the western part of the city, approximately 70 km away from the epicenter, and it killed about 1000 people in that area. The magnitude of the earthquakewas 7.4 by the U.S. Geological Survey (USGS) and Kandilli observatory, which operate a seismic network in the region.

The surface rupture caused by the earthquake consists of five segments (Figs. 3 and 4). The Hersek, Karamürsel–Gölcük, İzmit–Sapanca Lake and Sapanca–Akyazi segments had total length of 115 km. They are separated by releasing (pull-apart) step-overs of 1–4 km in width. The Karadere segment at the eastern end, which was triggered by the first main event (Pınar *et al.,* 2000), extends 30 km between Akyazi and Eften Lake in the south of Gölyaka with the orientation of about N65°E. The maximum offset throughout the surface break was measured on the Sapanca–Akyazi segment near Arifiye, east of Sapanca, where the fault displaced

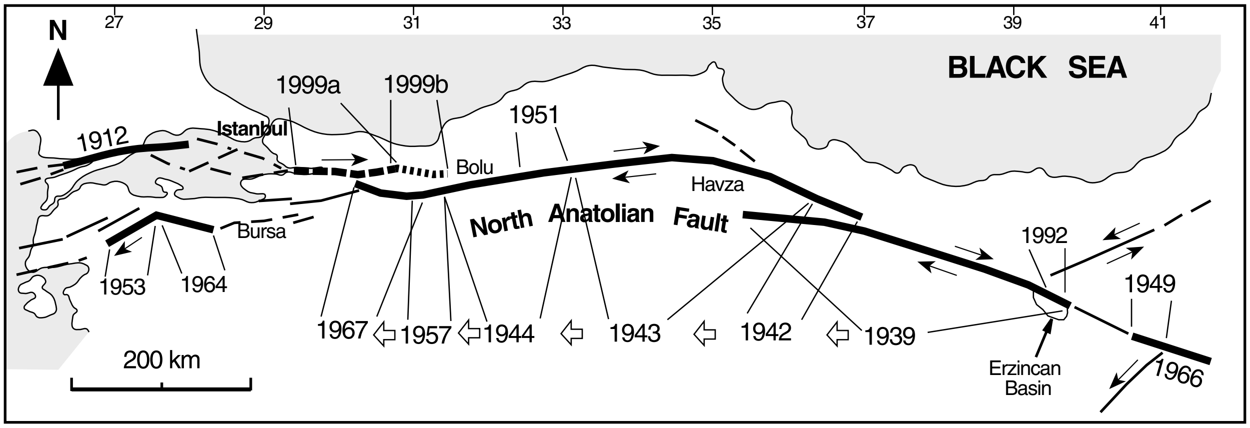

Figure 1. The westward migrating earthquakes since 1939 along the North Anatolian fault.

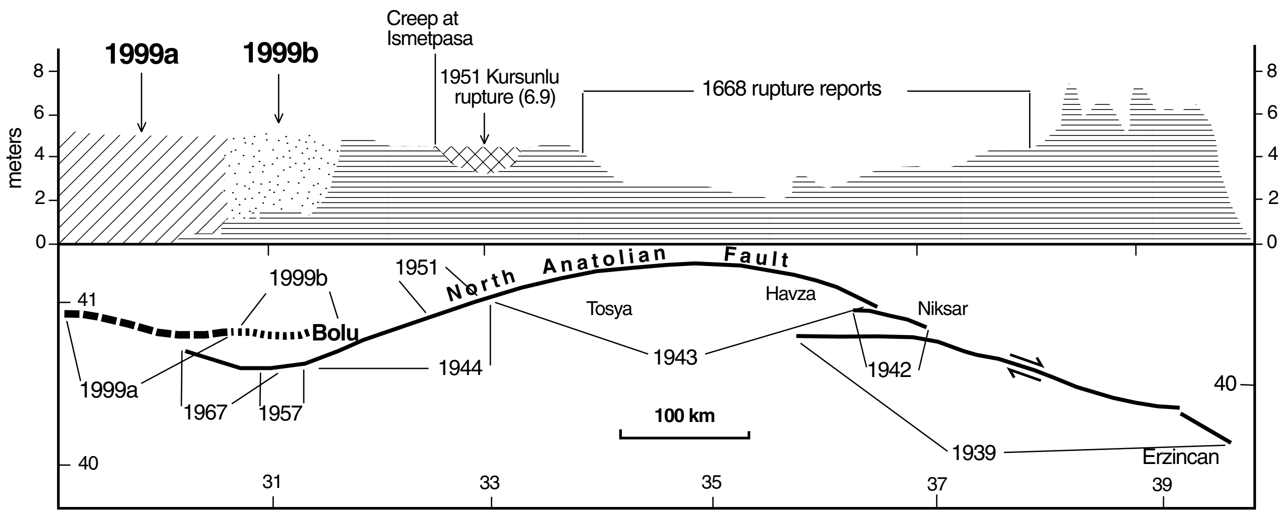

Figure 2. Slip distribution caused by the migrating earthquakes since 1939 along the North Anatolian fault (modified from Barka 1996).

a road and a poplar tree line by 5.2 m. The maximum displacement on the Karadere segment was about 1.5 m. The surface rupture expressed almost pure right-lateral strike slip, and the fault plane is nearly vertical in most places. The major aftershocks (M $\geq$4) were located in the Düzce area, south of Adapazarı, and in Sapanca, İzmit, and the Çınarcık area.

At Değirmendere, a small town in west of Gölcük, the surface breaks cut the toe of a fan delta where the center of the town was located, collapse of the fan delta caused a slump measuring 300 m long and 100 m wide, and part of the town center slid under the water, including a hotel and several shops and restaurants. At another fan delta east of Gölcük, which is located within the step-over area, the fault produced a 2-m-high normal fault scarp. Rupture on this connecting normal fault had an 8 m high relic scarp, suggesting occurrence at least three previous events besides the 1999 event. The two ends of the surface break terminated at the releasing step-over at the Karamürsel and Eften Lake.

Historical Earthquakes

The 1943 *M* 6.4 Hendek earthquake occurred within the rupture zone of the 1999 earthquake. However, earlier earthquakes in 1719, 1754, 1878, and 1894 occurred in the Gulf of İzmit region (Ambraseys and Finkel, 1991, 1995) (Fig. 5). The 1719 earthquake caused the death of 6000 people, in the Gulf of İzmit, İstanbul, and Adapazarı regions (Ambraseys and Finkel, 1991). There is little information about the 1878 earthquake, which caused considerable damage and loss of life in the Sapanca and Adapazarı regions. The 1894 earthquake caused damage and loss of life (1400 people) from İstanbul to Adapazarı (Ambraseys and Finkel, 1991); however, the 1894 earthquake is more likely located in the

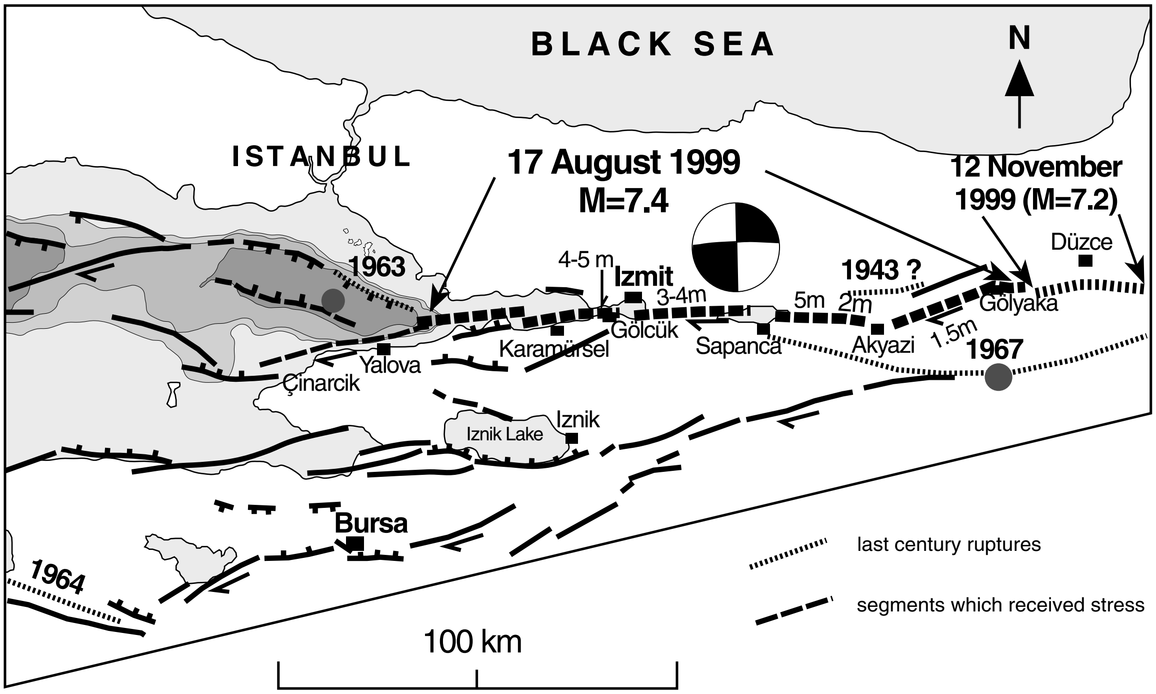

Figure 3. The map shows the extent of the 1999 ruptures and the 1943, 1963, 1964, and 1967 ruptures and the segments that received stress. Focal mechanism taken from Harvard.

Çınarcık basin and Hersek–Yalova segment. The 1754 earthquake appears to be similar in size and about the same location as 1894. The rupture zone for this earthquake is believed to be located either on the Yalova segment or the Çınarcık basin. Among these earlier earthquakes, the 1719 earthquake is perhaps most similar in magnitude and location to the 1999 earthquake, although it might have occurred closer to İstanbul. The remaining two earthquakes, in 1754 and 1894, probably occurred in the area between western part of the Gulf of İzmit and Adapazarı.

The Rupture Zone

Five segments produced surface breaks during the 17 August İzmit earthquake, which are separated by releasing step-overs. From west to east, these are the Hersek, Karamürsel–Gölcük, İzmit–Sapanca Lake, Sapanca–Akyazi and Karadere segments, respectively. The slip distribution along each segment is shown in Figure 5. Some details of each segment are summarized in the following sections.

The Hersek Segment

The Hersek segment that extends between Hersek delta and north of Yalova defines the westernmost part of the 17 August rupture zone (Armijo *et al.,* 2000; Wright *et al.,* 2000) and has an orientation of N80°E. Here the fault has a 25-m-high pressure ridge (Witter *et al.,* 2000). West of the ridge on the road to Hersek village, some minor cracks were observed. Along the eastern margin of the delta, east of the ridge, there is a concrete wave breaker and an old house where some cracks and slight rotation of the concrete blocks may indicate minor displacement.

Between the Hersek delta and Yalova, a number of minor, secondary faultlike features were observed. The most continuous one among these faults crosses an airport for over a distance of 1 km on the Taşköprü delta. They are a set of en-echelon, open cracks in extensional nature striking east–west on average. There is no significant lateral movement on these cracks. The cracks have individual lengths reaching tens of meters and widths of up to 8 cm, and overall they form a down-to-the-north step that reaches a maximum height of 20 cm. These features may well correspond to second- and/or third-order ruptures interconnected to the main rupture zone located offshore, just to the north of the delta.

The Karamürsel–Gölcük Segment

The trace of the Karamürsel–Gölcük segment runs mostly offshore and parallels the escarpment along the coastline between Karamürsel and Değirmendere for about 20 km. Recently acquired bathymetry and seismic profiles indicate a nested pull-apart (Lettis *et al.,* 2000) and a negative flower structure about 3 km in width. During the earthquake, many slumping and lateral spreading occurred at many localities along the coastline. Değirmendere experienced dramatic collapse and subsidence of the seaside. Again these features may be attributed to the nearby fault rupture. The fault clearly enters onto land at the west side of Gölcük, crossing 2 km of the town, the port, and the Turkish Navy

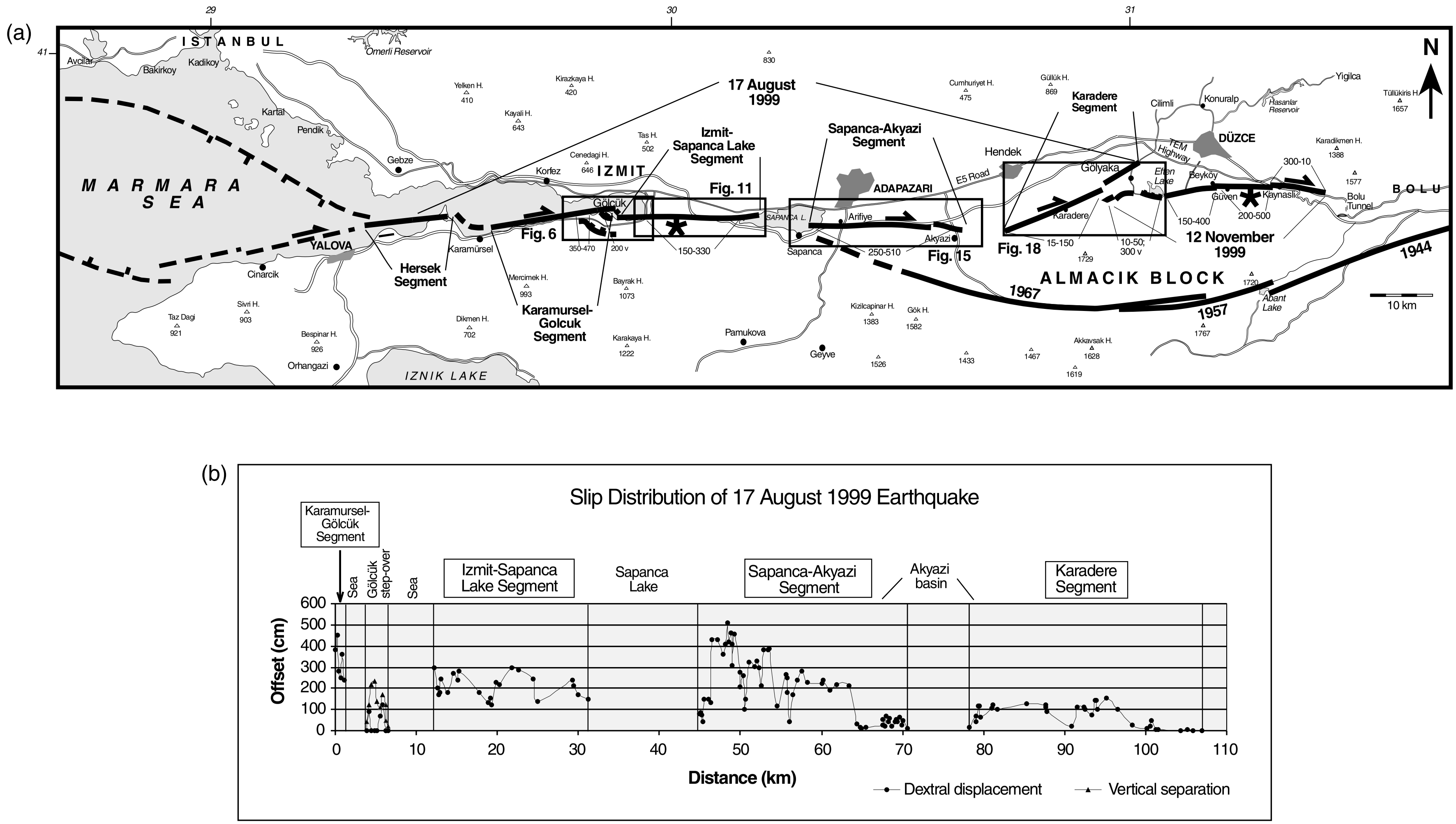

Figure 4. (a) Segmentation and (b) slip distribution diagram of the 17 August 1999 İzmit earthquake. Stars show epicenters of August and November events.

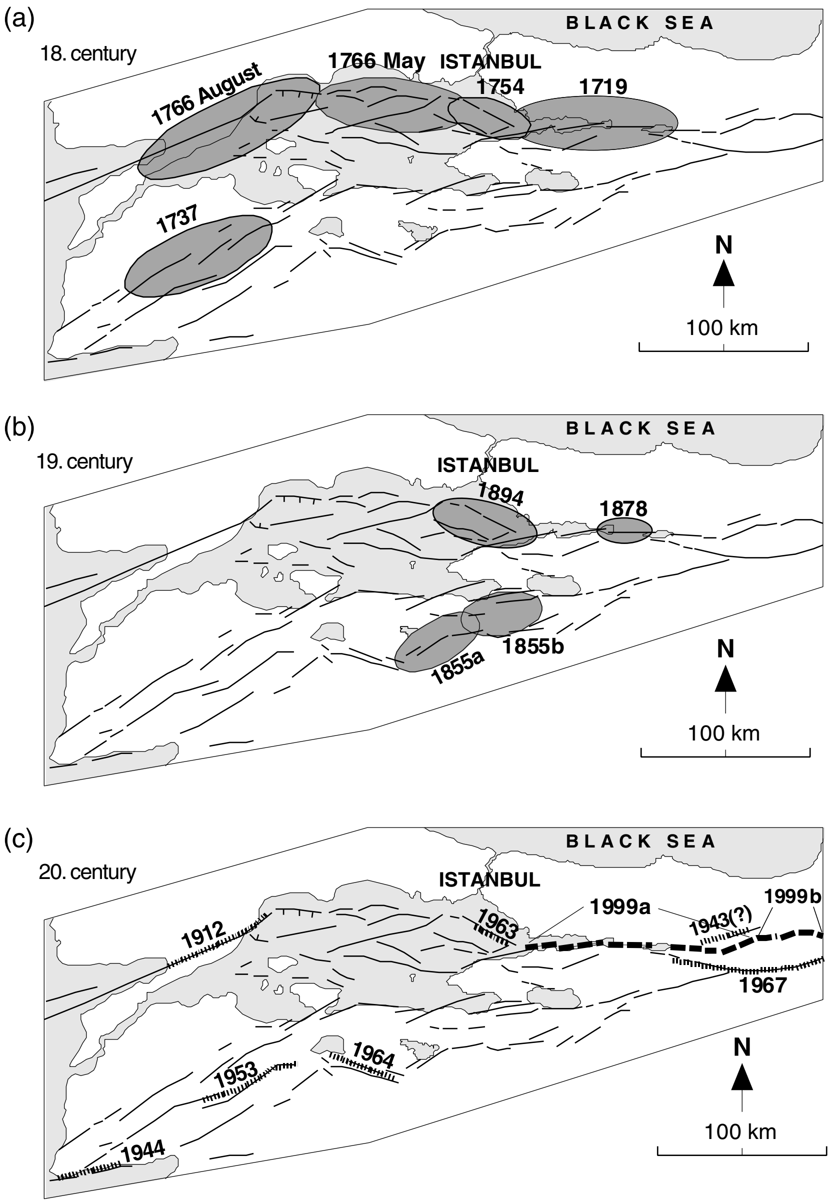

Figure 5. Distribution of earthquakes in the last 300 yr in the Marmara Sea region. (a) Eighteenth century; (b) nineteenth century; (c) twentieth century. Ellipses are historical earthquakes. Interpreted from Ambraseys and Finkel (1991, 1995). Dashed lines are the 17 August 1999 İzmit earthquake and 12 November 1999 earthquake, and dotted lines are previous twentieth-century earthquakes.

base (Fig. 6). From the Navy base port eastward, the fault break veers southward, goes under the sea for about 1 km, and apparently connects with a normal fault that strikes northwest–southeast, and so the rupture enters again on land at the eastern district of Gölcük.

Significant, consistent right-lateral slip was observed across streets, buildings, and military facilities in Gölcük. The jetty on the west side of Gölcük was offset by 450 cm. The largest offset we documented is very well constrained at the western side of the Navy base, where the street, the sidewalks, and the straight wall of the Navy base are cut nearly orthogonally by the fault (Fig. 6b; site 2). At this site the fault divides into two parallel breaks about 25 m apart. Our detailed survey shows no vertical offset, and the net right-lateral slip resolved along the local fault strike (N85°E) is 470 cm (Fig. 7; site 2).

Between the western wall of the Navy base and the port, the break follows the southern side of a 600-m-long, 50-m-high, ridge. The port area crossed by the fault corresponds mostly to artificial embankments between two small bays. The break is seen as a narrow (1 m wide), linear set of mole tracks striking N85°W for about 500 m. Two sites surveyed along this stretch of the fault yield similar right-lateral offsets of 370 cm and 350 ± 40 cm. The measurements were taken where it offsets a large water main (Fig. 8; site 3a) and where the fault crosses a straight, long pier equipped with paired rails for port cranes (Fig. 8; site 3b).

Gölcük Step-Over Normal Fault. The releasing step-over between the Karamürsel–Gölcük and İzmit–Sapanca Lake segments corresponds to fault separation of about 2 km. A number of northwest–southeast-striking faults, both on land

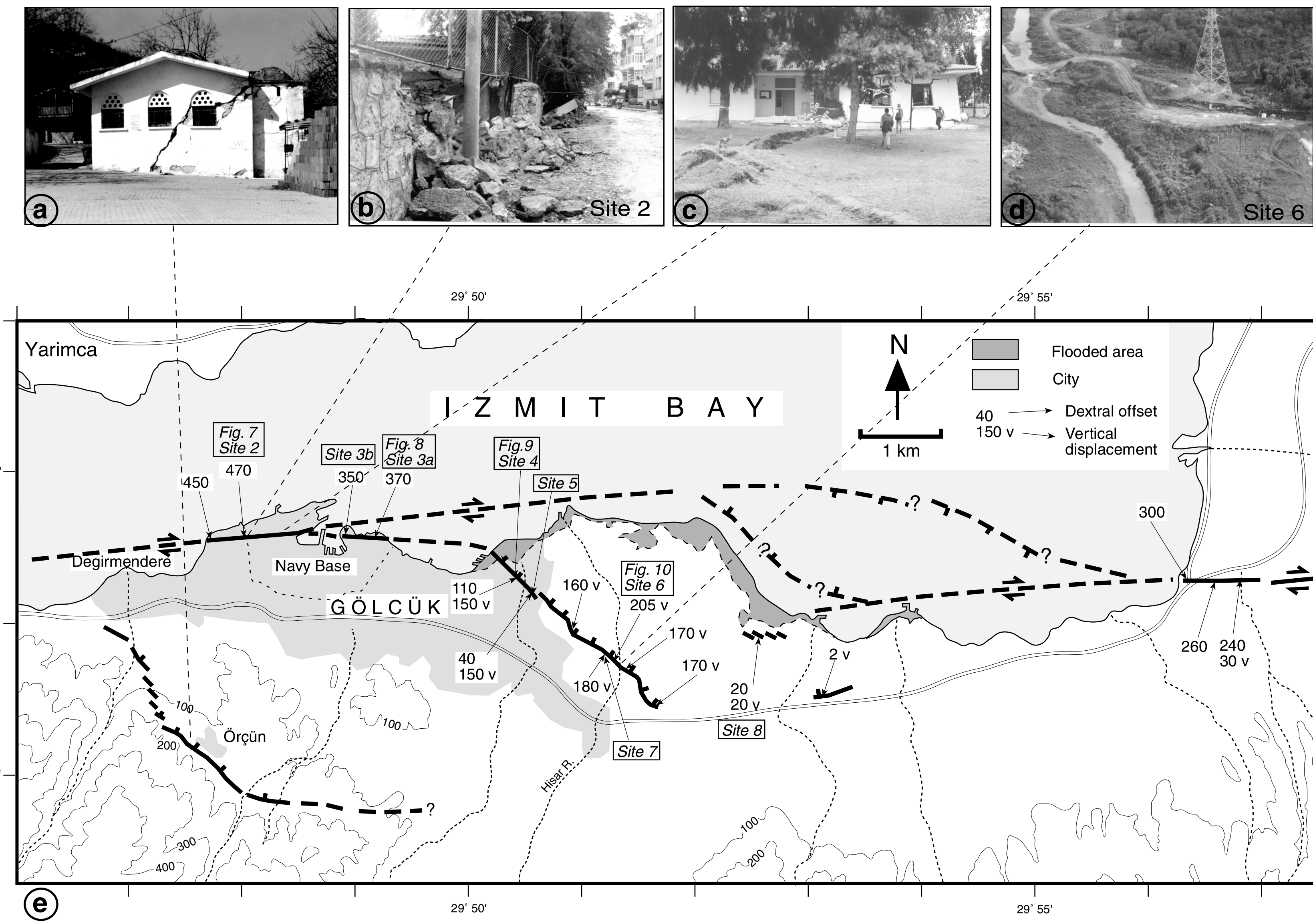

Figure 6. (a) The heavily damaged old Turkish bath at Sultanbaba. (b) Two-strand surface rupture right-laterally offsets the Navy wall 4.7 m in Gölcük. (c) Surface rupture crossing the Navy entrance building in Gölcük. (d) Gölcük normal fault with 2-m vertical offset in the Ford Factory area. (e) The 1999 earthquake rupture in the Gölcük–İzmit Bay step-over. Several fault segments with northwest–southeast strike and normal component of slip have ruptured both on land near Gölcük, and probably offshore in the İzmit Bay. Numbered sites indicate observations discussed in the text. Extent of flooded area in the hanging wall of Gölcük normal fault was mapped by comparing SPOT panchromatic scenes acquired before (21 July 1999) and after (20 August 1999) the earthquake. Segmented lines offshore are extrapolated from strike-slip fault geometry on land. Offshore faults with normal slip (inferred from bathymetry and shallow seismic) (Sengör *et al.,* 1999) are consistent with observation of tilt on land.

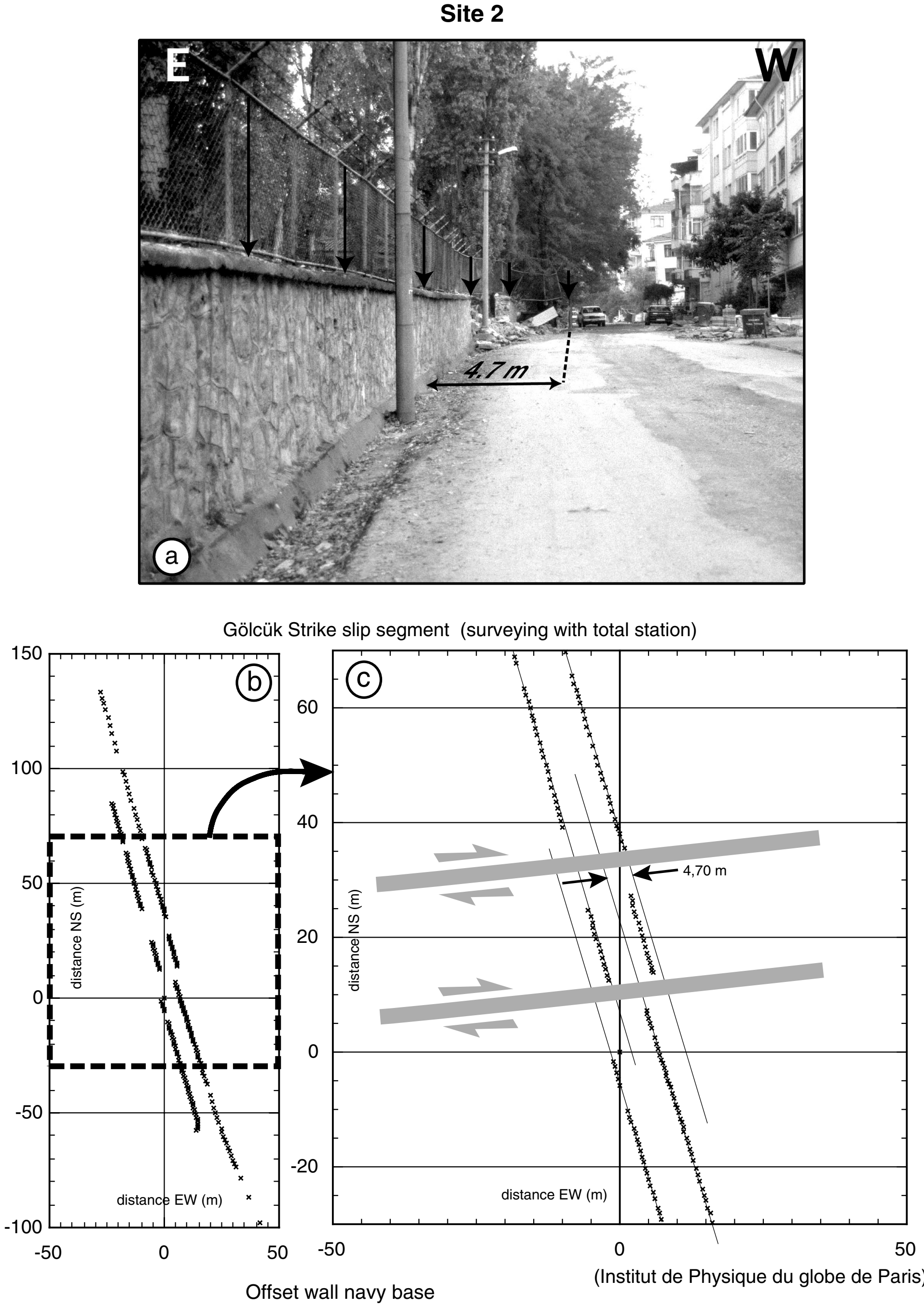

Figure 7. Right-lateral slip in Gölcük (site 2, for location see Fig. 6). (a) View of the offset street and the wall by the Navy base. Arrows point to top of wall. (b) Map of the survey. (c) Detail of the survey showing consistent offset by 4.7 m of the wall and sidewalk edge.

and offshore, appear to contribute to absorb the strain associated with this step-over. Two of the faults located on land display unequivocal coseismic breaks with down-to-the-northeast movement, indicative of normal faulting and of northeast–southwest extension with approximately 100 cm of strike-slip component.

The normal fault across the eastern part of Gölcük is the one with the greatest coseismic displacement and the strongest geomorphic impact. It produced a scarp with total length of 3.5 km and clear composite normal and right-lateral displacement. Measured throws along the normal fault scarp average about 150 cm and reach locally 205 cm (Figs. 6, 9, and 10; sites 4 and 6). Normal faulting also caused local uplift across riverbeds. The most impressive is the approximately 2-m-high waterfall created across the Hisar river (Fig. 6d). The right-lateral component of the slip

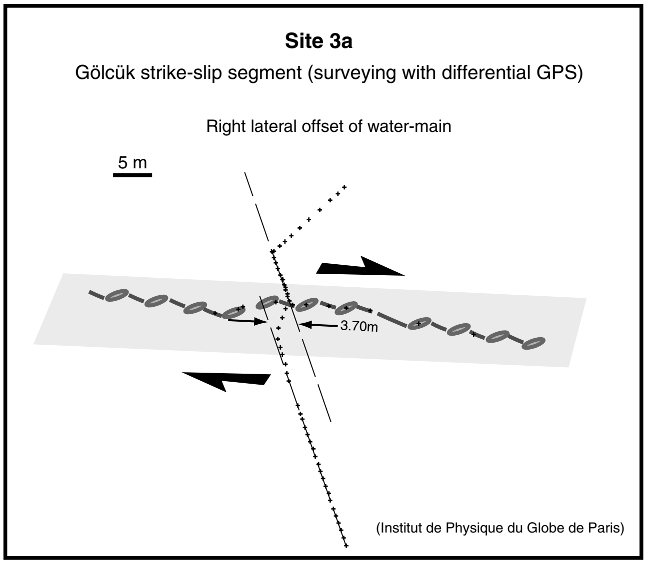

Figure 8. Right-lateral offset of water main (for location see Fig. 6).

is well constrained in some sites. The more accurate is site 4 where an offset wall topped by a fence with regularly spaced poles provides the complete description of the slip vector (Figs. 6 and 9). There, the fault strikes N40°W, and the right-lateral, transverse (horizontal extension), and vertical components are 110 ± 20 cm, 45 ± 10 cm, and 150 ± 10 cm, respectively. An estimate with consistent proportion of vertical and transverse (150 cm and 40 cm) but smaller right-lateral (40 cm) offsets is obtained at site 5 (Fig. 6), where one of the branches of the break cuts across the corner of a house.

The central part of the break along the Gölcük normal fault coincides with a larger pre-existing scarp. This feature is clearly seen at site 7, where the 1999 event produced a scarp 1.8 m high, which corresponds to about one-third of the visible cumulative displacement at this site (Fig. 6). Overall, however, the maximum height of the cumulative scarp is 8 m, which implies a pre-existing scarp of about 6 m. Thus, our observations suggest that at least three previous events with similar slip to the 1999 earthquake may have ruptured the Gölcük normal fault. We conclude that the

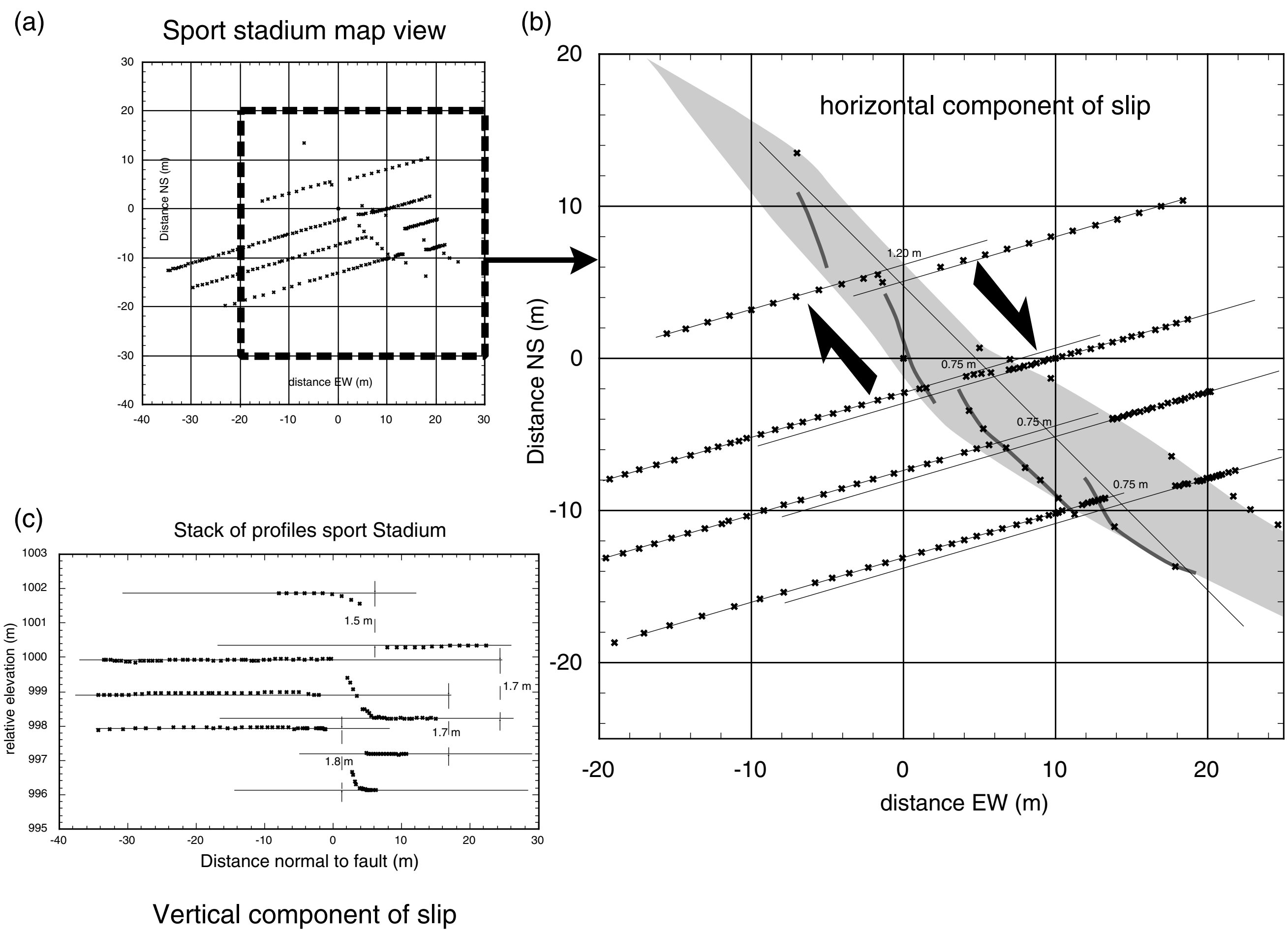

Figure 9. (a) Map view of sport stadium, (b) horizontal, and (c) vertical components of slip at site 4 (Gölcük normal fault) (for location see Fig. 6).

area presents good potential for investigation of past earthquakes with trenching techniques.

The break along the Gölcük normal fault ends abruptly to the southeast, without apparent connection with any other earthquake break (Fig. 6). Moreover, the area between this termination and the place where the İzmit–Sapanca segment enters the Gulf is almost devoid of evident tectonic breaks. However, a set of east–west-striking en-echelon cracks can be followed over a length of 0.5 km near the coast (site 8), which implies 20 cm of down-to-the-north vertical movement and 20 cm of right-lateral slip, consistent with the overall kinematics.

The other normal fault that broke on land during the earthquake parallels the Gölcük fault 4 km southwest of it, uphill from the village of Örçün (Fig. 6). The Örçün fault marks the contact between hanging-wall sediments of the Neogene and footwall basement rocks and runs at the base of a sharp mountain front with prominent triangular facets. The surface break was almost continuous for 3 km and consisted of open cracks and small scarps with up to 10–20 cm of down-to-the-northeast, normal slip. It crossed roads and fields and heavily damaged the old Turkish bath of Sultanbaba (Fig. 6a).

A spectacular effect of the earthquake was the sudden drowning of the bay-shore avenue and of many houses and buildings in the eastern district of Gölcük. Although gravity sliding of the soft sediments in the littoral zone around the large alluvial fan east of Gölcük (Hisar river delta) cannot be neglected, hanging-wall subsidence may be partly responsible of the flooding along that coastline (Fig. 6). The relative importance of tectonic subsidence and tilt in the fan area can be evaluated with geodetic data from a local network (provided by Ford Otosan factory). Our preliminary analysis of the data indicates that the net subsidence of the coastline at 2-km distance from the Gölcük normal fault is about 0.5 m, and the outward (southwest) tilt is on the order

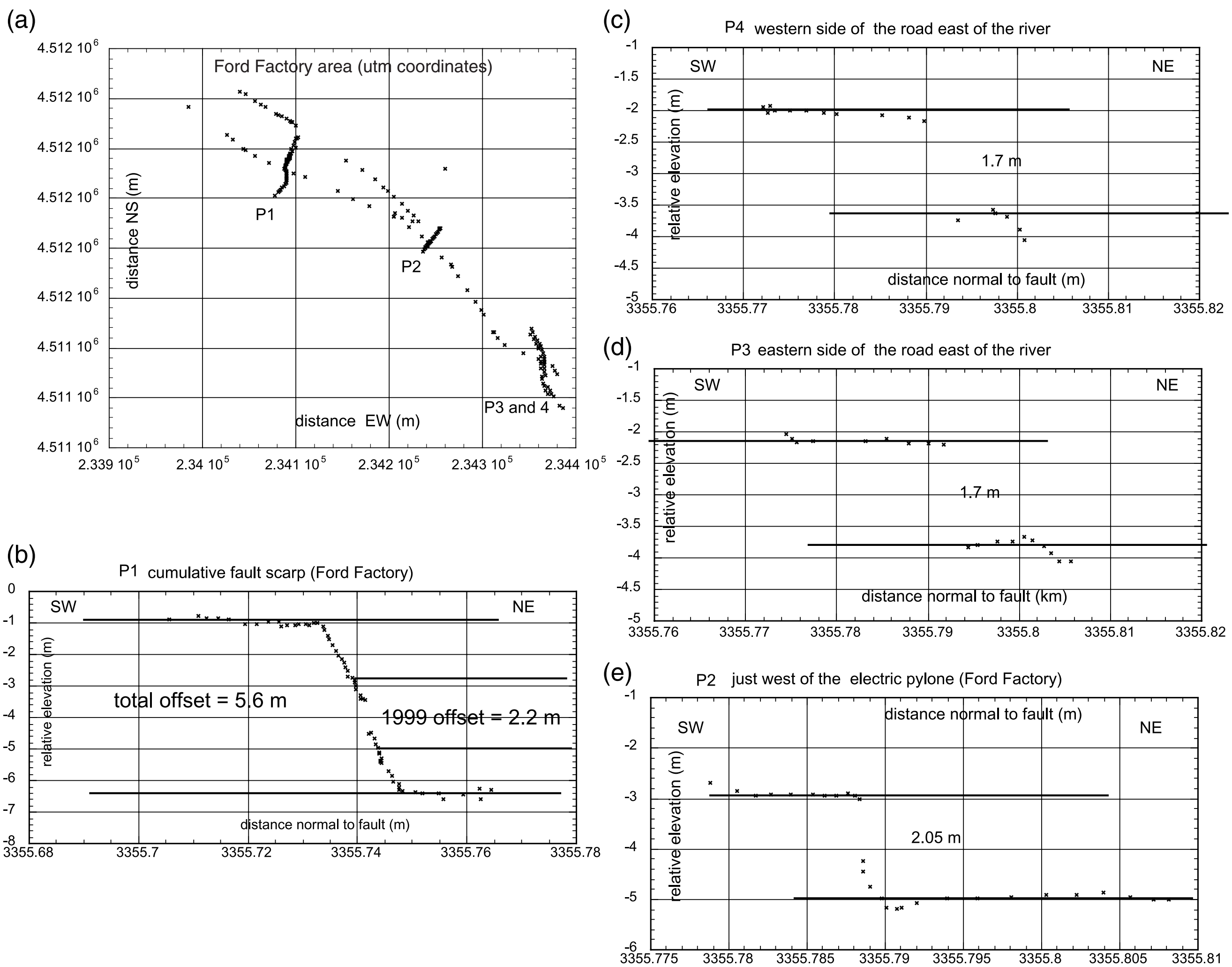

Figure 10. Slip measurements at Gölcük normal fault (site 6, for location see Fig. 6). (a) Map view of Ford Factory area showing profile locations, UTM, universal transverse mercator; (b) P1, cumulative fault scarp; (c) P4, western side of the road east of the river; (d) P3, eastern side of the road east of the river; (e) P2, just west of the electric pylone.

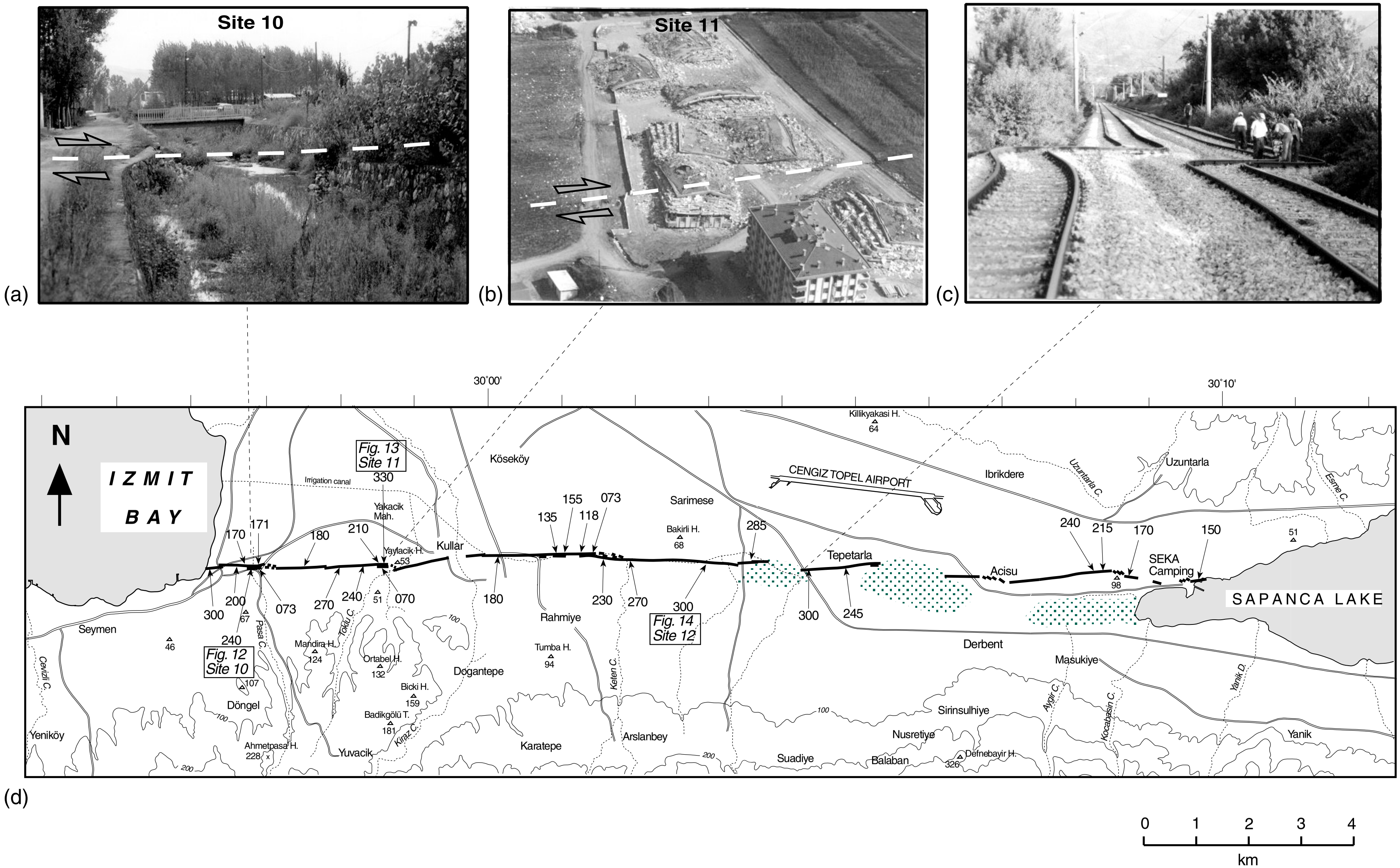

Figure 11. (a) Offset canal; (b) collapsed apartments and surface rupture; (c) offset railway; (d) slip distribution and rupture geometry of the İzmit–Sapanca Lake segment. Numbers with arrow on the fault show dextral offsets. Dotted areas are swamps.

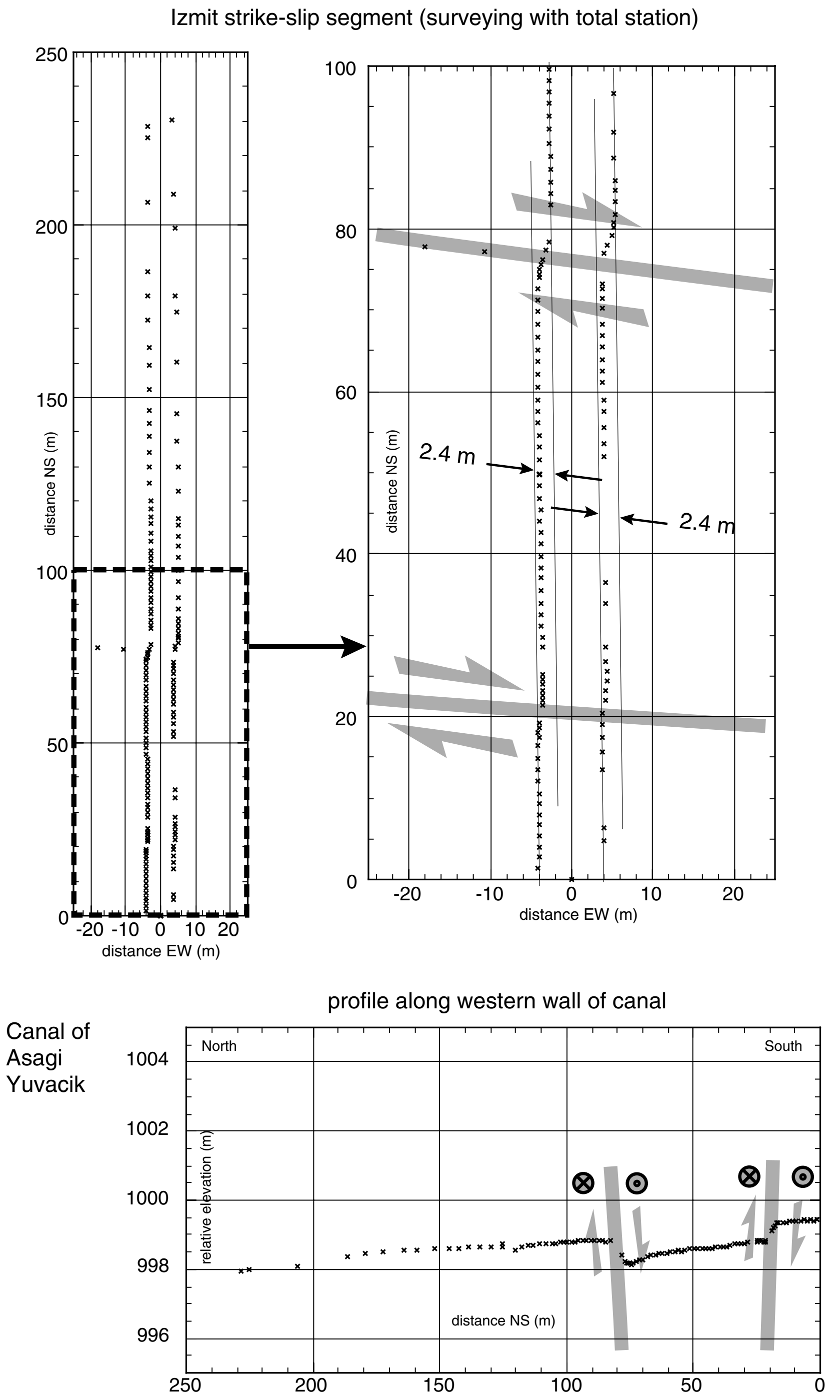

Figure 12. Total station survey at canal in Asagi Yuvacik village (site 10, for location see Fig. 11).

of 0.1%. We interpret the coseismic tilt and hanging-wall subsidence as indicative of block faulting in the step-over region. The Hisar river delta would be sitting on top of a block bounded to both to the southwest and the northeast by similar faults. Thus, the evidence is suggestive of coseismic rupture of an offshore fault similar to the normal fault crossing Gölcük. In addition, the recently acquired bathymetry and seismic profiles in the Gulf of İzmit (Sengör *et al.,* 1999) indicate southwest-facing scarps associated with a fault with down-to-the-southwest, normal slip (Fig. 6). This fault could have also ruptured during the earthquake. Considered together, this fault and our deduced offshore fault appear to form a 1.5-km-wide pull-apart basin located just east of the Hisar river delta. The amount and proportion of lateral and normal slip on the offshore faults remain to be determined.

The İzmit–Sapanca Lake Segment

The 1999 surface rupture between the İzmit Bay and Sapanca Lake is called the İzmit–Sapanca Lake segment (Figs. 4 and 11). The total length of the İzmit–Sapanca Lake

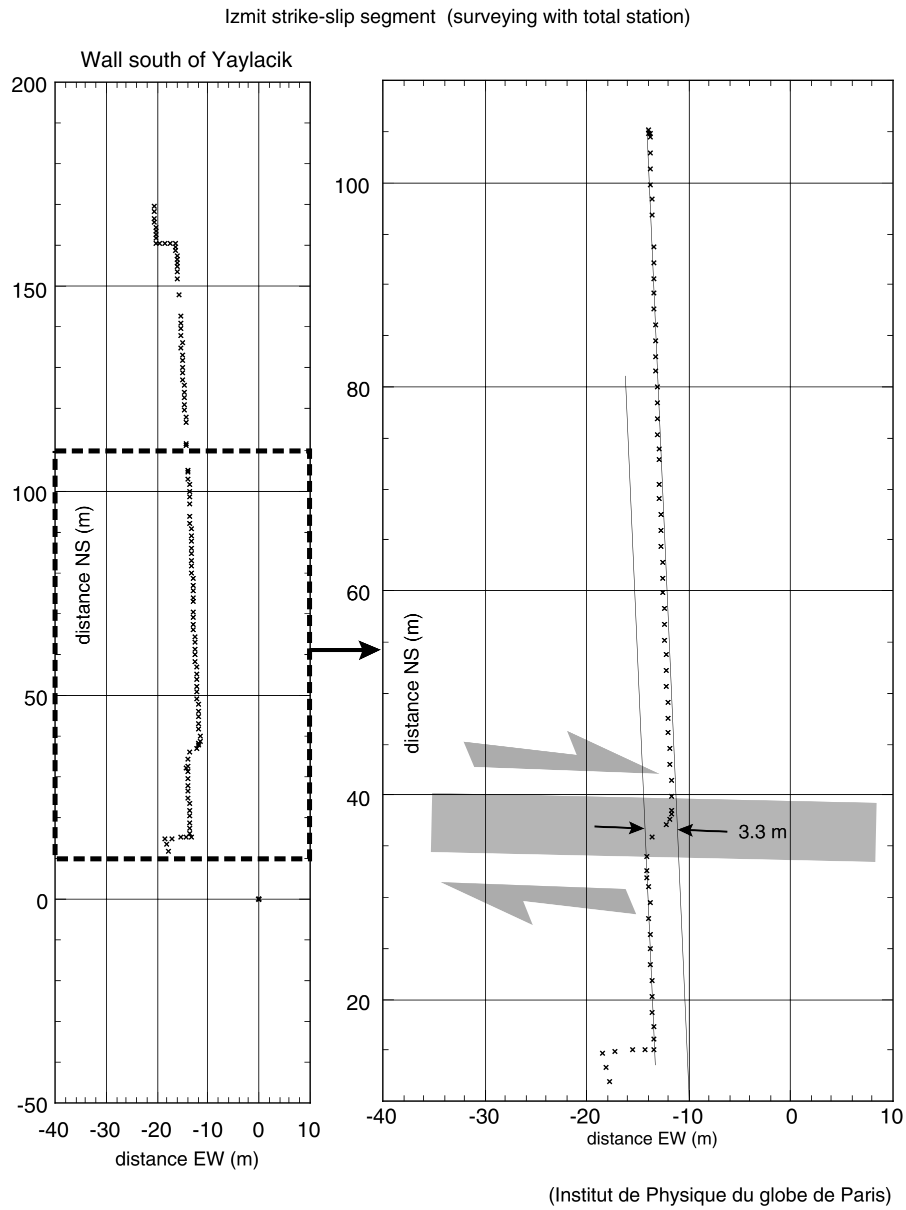

Figure 13. Survey with total station on western wall of apartment complex (site 11, for location see Fig. 11).

segment is about 20 km on the land, and it starts at the eastern end of the İzmit Bay in the west and ends in the northwest corner of the Sapanca Lake in the east. The İzmit–Sapanca Lake segment is first seen on land as a 30-m-wide deformation zone in unconsolidated beach sediments. About 200 m farther east, it becomes a simple surface rupture with an orientation of N80°E. The dextral displacement varies from 180 to 300 cm within the first 4 km to the east of İzmit Bay. The surface rupture continues east with an orientation between N75°E and N80°W. Measured dextral displacement varies between 120 and 330 cm along the rupture zone. The average slip on the İzmit–Sapanca Lake segment is about 250 cm.

Dextral offsets are very clear and measurable on offset roads, fences, buildings, irrigation channels, small stream beds, and aligned trees that intersect by the rupture zone. At three sites, the coseismic slip is especially well constrained by surveys of long markers across the fault zone. At site 10 (Figs. 11 and 12), the fault cuts orthogonally a large (300-m-long, 8-m-wide), straight canal that is made of concrete. There, the rupture splits into two parallel breaks 60 m apart, confining a zone with minor distributed cracks. Total dextral slip is 240 cm, but a net vertical, down-to-the-north offset of 30 cm is also clear. This suggests a component of normal faulting, consistent with the morphology and the pull-apart structure of the İzmit Bay. The other well-constrained case is a set of apartment blocks (that collapsed during the earthquake) where the rupture crosses and the straight wall flank-

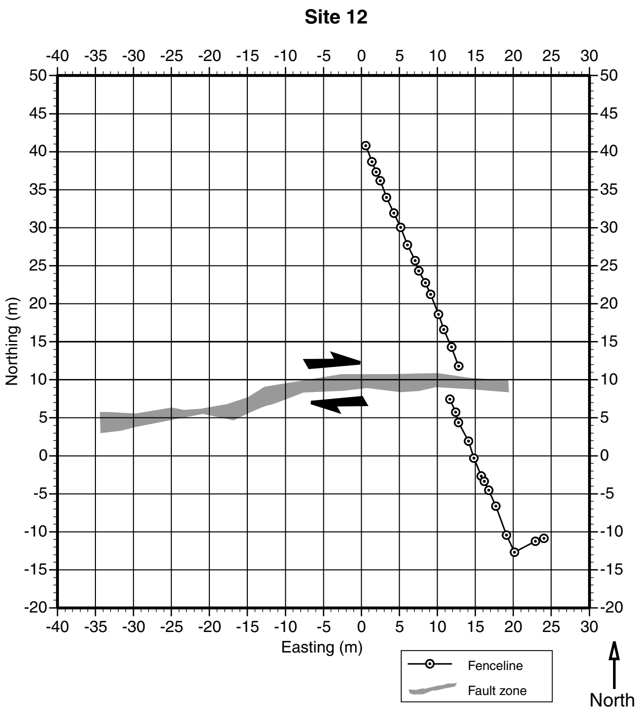

Figure 14. Survey with total station on a garden fence at south of Sarimese village (site 12, for location see Fig. 11).

ing them to the west (Fig. 13; site 11). The net strike-slip offset of the wall is 330 cm. At site 12 (Figs. 11 and 14), 2 km west of Tepetarla village, a garden fence is cut by surface rupture nearly orthogonally. The coseismic dextral slip at this site is 300 cm.

Much larger offsets on some topographic features (such as small hills and stream beds) indicate that the 1999 surface rupture follows previous earthquake faults. For example, a small hill is offset about 400 m dextrally about 1 km west of Kullar village. Similarly, a creek is offset about 50 m dextrally in west of Kullar village. Surface rupture indicates a narrow (0.5 to 3 m) deformation zone in general. However, the width increases up to 100 m, especially in marshy areas. Just west of the Tepetarla village, the rupture zone offsets the railway about 3 m, and the rupture zone goes right through the village. To the west and east of Tepetarla, there are two swamp areas in right-stepping sections of the fault. The surface rupture along the İzmit–Sapanca Lake segment closely matches the previously mapped trace (Barka, 1997).

Near the eastern end of this segment, the orientation of the rupture zone is N80°E. Although it enters the northwestern corner of the Sapanca Lake in the land, some local subsidences along the northern side of the lake indicate that this segment most probably continues farther east close to the northern coast of the lake. This observation is important because it provides evidence for a right step-over between the İzmit–Sapanca Lake segment and the Sapanca–Akyazi segment and suggests that the Sapanca Lake is a pull-apart basin.

The Sapanca–Akyazi Segment

A joint-led team (USGS, Southern California Earthquake Center, and İTU) mapped the geometry and slip characteristics of the approximately 26-km Sakarya fault section resulting from the 17 August 1999 İzmit earthquake. This reach of the rupture traverses the Sakarya River plain from Lake Sapanca in the west to the town of Akyazi in the east (Fig. 15). The Sapanca–Akyazi segment is typically expressed as a narrow (2–8 m wide) rupture zone with slip ranging from less than 1 m to about 5 m of right-lateral motion. In general, the Sapanca–Akyazi segment has an overall east–east-southeast trend and is expressed as a broad arcuate shear zone consisting of multiple kilometer-scale sections linked by extensional (right) step-over zones. At several localities along the fault, the strike and style of individual fault strands vary significantly, especially where the fault enters a step-over zone and near-fault terminations. Commonly, these areas were accompanied by a component of vertical (normal) slip with no preferred down-dropped direction. The acquisition of a large number of high-quality slip measurements were made possible due to the large number of cultural features that were crossed by the fault, including roads, fences, cornfields, poplar groves, and manmade canals. The dextral slip reaches a maximum of 500 ± 20 cm near Arifiye, based on offset rows of evenly spaced poplar trees and offset of small village roads (Figs. 15 and 16; site 13). Another survey site is at the eastern stream bank of the Sakarya River and lined trees. Two parallel surface ruptures offset the bank and trees by 330 cm (Figs. 15 and 17; site 14). The rupture zone goes through a gas station offsetting the two sets of gas pumps about 450 cm without causing any damage to either. To the east of Arifiye the slip decreases gradually over a distance of 16 km to approximately 2 m, south of Kazanci. There, the rupture makes a 1-km-wide step to the north (restraining step-over), after which slip again increases up to 1 m. Farther east, the slip dies toward its termination about 1 km east of Akyazi. To the east of the Sapanca–Akyazi, the rupture steps southward to the Karadere segment, along which rupture continued to the northeast.

The Karadere Segment

The surface trace of the Karadere segment begins about 6 km east of Akyazi and extends eastward about 30 km to its termination along the south side of Eften Gölü, about 5 km southeast of the town of Gölyaka (Fig. 18). This segment is distinct from the east-southeast-trending Sapanca–Akyazi segment: there is an abrupt change in strike to north-northeast for the Karadere segment as well as an approximately 6-km-long section east of Akyazi, where we did not recognize surface rupture. Between approximately 6 and 8 km east of Akyazi, slip increases from surface fractures with a few centimeters of displacement to offsets of approximately 100 cm of dextral slip. A number of high-quality slip measurements were obtained using dextrally offset cultural features

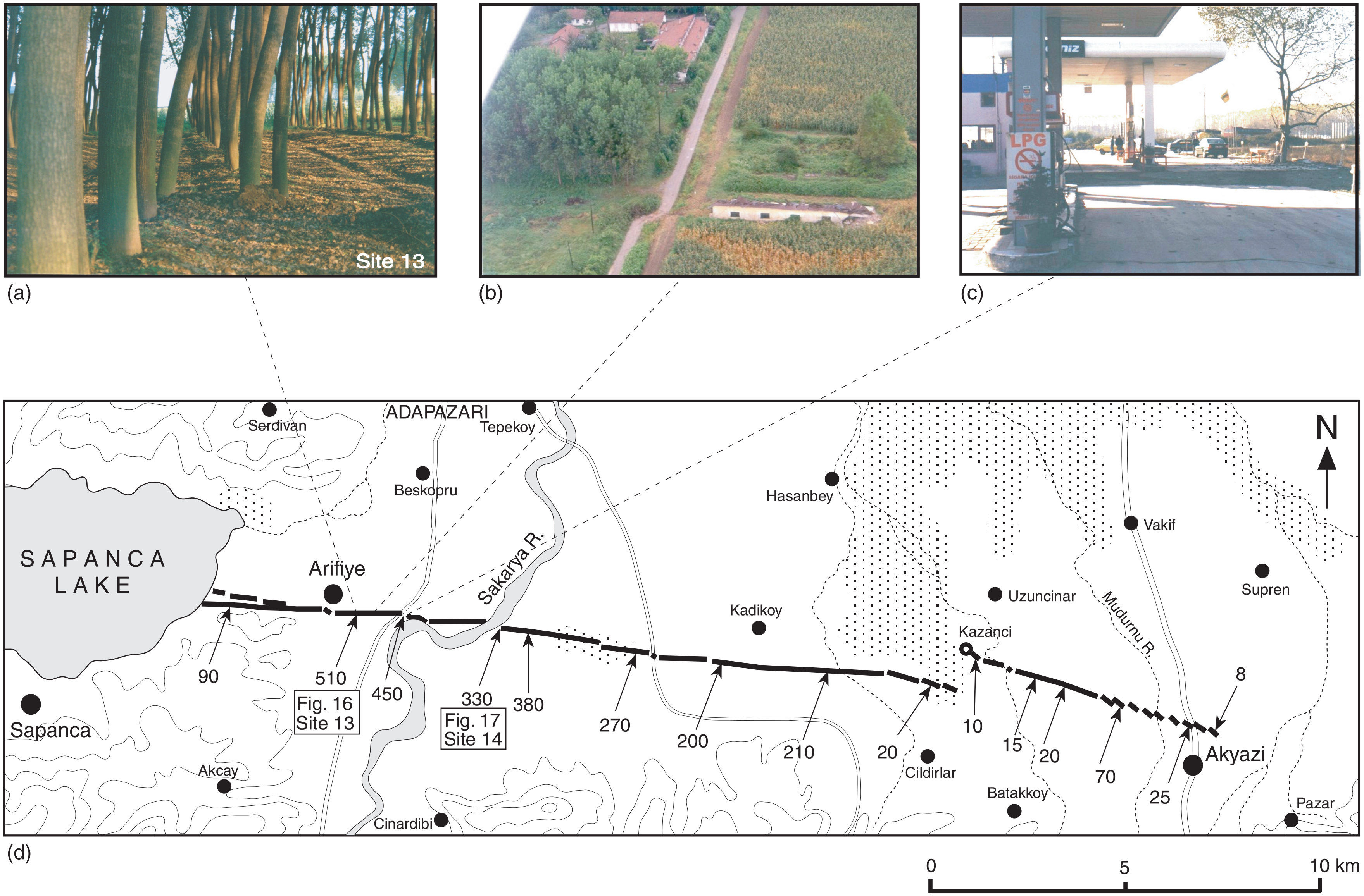

Figure 15. (a) Offset lined poplar trees. (b) Offset village road. (c) Gas station cut by rupture offsetting the two sets of gas pumps without causing any damage to either. (d) The rupture map of Sapanca–Akyazı segment. The numbers on the fault show dextral offsets. Dotted areas are swamps.

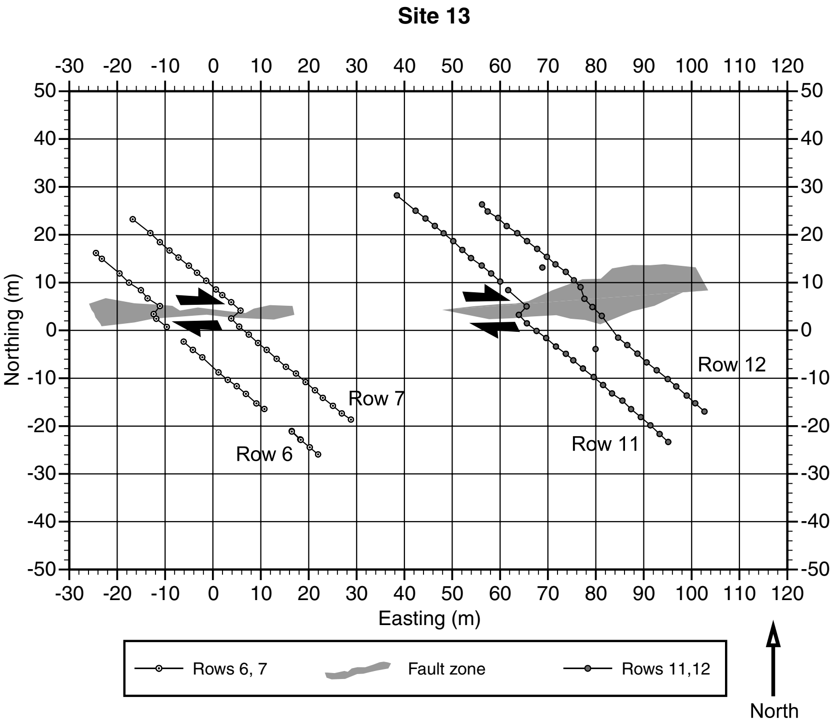

Figure 16. Survey with total station on offset poplar trees at the east of Arifiye (site 13, for location see Fig. 15).

including roads, fences, and rows of planted trees. In contrast to other segments that ruptured during this earthquake, slip along this segment is typically less, averaging about 120 cm in the central reach of the fault, with a maximum observed displacement of about 150 cm, which occurs about 7 km southwest of Gölyaka.

About 5 km southwest of Gölyaka, the fault steps about 1.5 km to the south. From there, the fault continues for another approximately 9 km farther east, where it terminates along the major range bounding fault that defines the south side of Eften Gölü. Slip along this far-eastern extent of the rupture ranges from less than 10 cm to as much as about 50 cm and occurs in the central portion of this reach of the fault.

In addition to the primary rupture, a 200- to 300-m-wide zone of surface cracking was also observed along a river levee, about 4 km norhtwest of Gölyaka. Many of these cracks exhibited small-scale dextral displacements in the range of several centimeters for individual cracks. It is not clear whether this is related to primary rupture, triggered slip, or is simply the result of shaking.

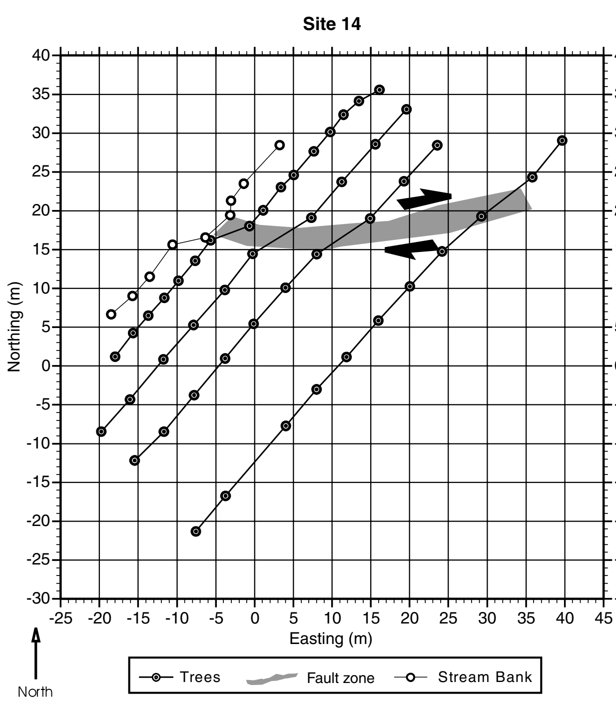

Figure 17. Survey with total station on eastern stream bank of Sakarya River (site 14, For location see Fig. 15).

Discussion and Conclusions

The rupture zone of the 17 August 1999 İzmit earthquake consists of five geometric segments, each of which is separated by releasing step-overs of 1–4 km width. The two ends of the rupture zone also have the same geometry. The step-over areas are expressed by lakes or basins within the Gulf of İzmit. Along the normal faults, which connect the strike-slip segments in the pull-apart areas, there was 235 cm maximum vertical offset. This amount could be more in the offshore areas in the İzmit–Gölcük basin and Karamürsel basin. At the pull-apart areas, the rupture zone widened and mountain front faults had 10- to 20-cm vertical offsets.

The surface rupture zone is terminated near the Hersek

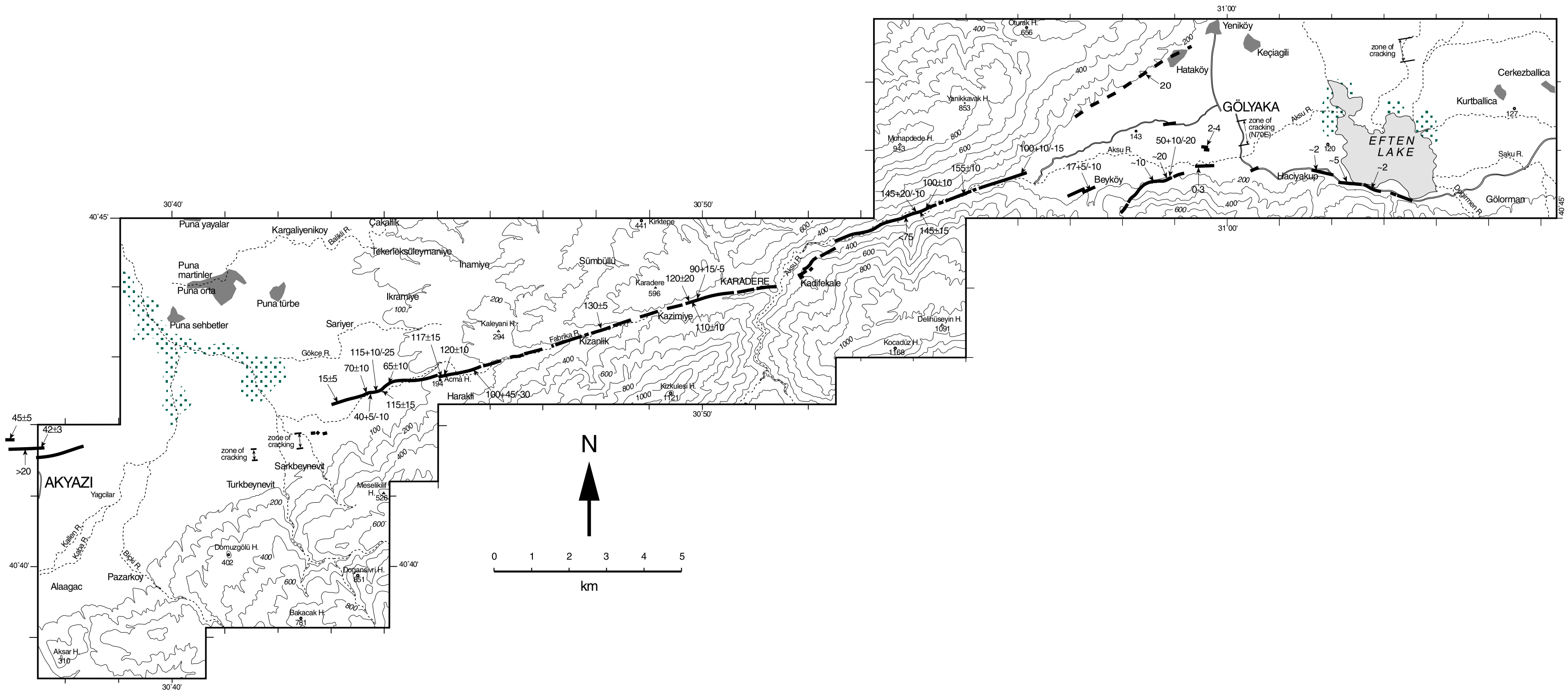

Figure 18. The extend of the Karadere segment. The numbers with arrow on the fault show dextral offsets. Dotted areas are swamps.

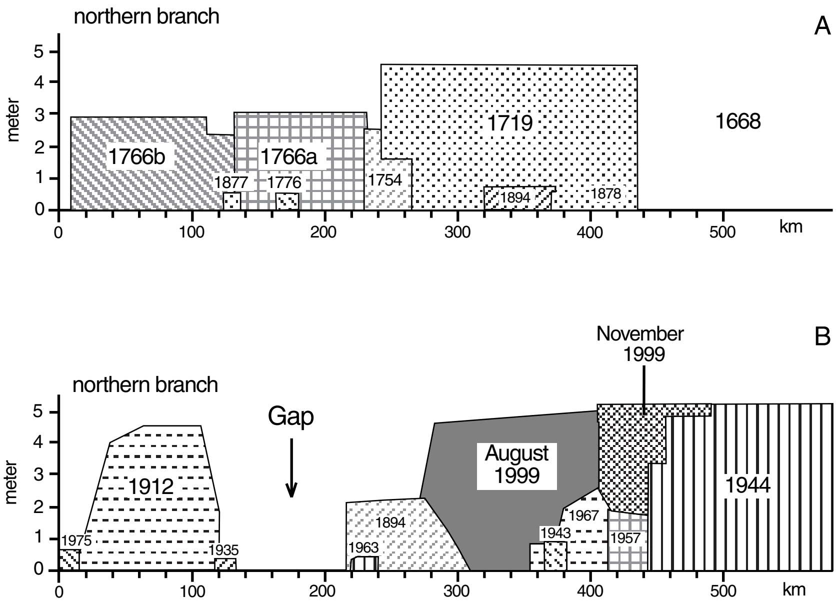

Figure 19. Earthquake activity along the northern strand of the North Anatolian fault since A.D. 1700. Modified from Hubert-Ferrari *et al.* (2000).

delta at the west end and at Gölyaka at the eastern end. The amount of slip at the surface, at both the western and eastern ends, at Hersek delta and south and north of Gölyaka, was not more than 5–10 cm. According to the GPS data, the rupture zone extended about 10 km west of the Hersek delta with 60-cm slip at depth (Reilinger *et al.,* 1999). The interferometry data revealed, on the other hand, 1.7–2 m slip for the same section at depth (Wright *et al.,* 2000; Armijo *et al.,* 2000). On the other hand surface data reveals that the rupture zone terminated near Hersek delta. Secondary extensional cracks observed in Taşköprü delta are not representative of the main rupture. The main conclusion for this data is that the rupture zone had a sharp slip decrease along the Hersek segment. Even though there might be few centimeters to just over 1-m slip at depth, we did not observe any significant displacement at surface.

The GPS studies (Straub *et al.,* 1997; McClusky *et al.,* 2000) indicates that the slip rate in this part of the North Anatolian fault is about 23 mm/yr, and about 20 mm/yr of this amount is taken up by the northern strand. In this section of the northern strand the last known large earthquake is the 1719 earthquake, since then 5- to 6-m slip could have accumulated on this segment. The maximum slip measured at the surface, 470 cm at Gölcük and 520 cm near Arifiye, are comparable with the amount that accumulated since 1719. Following the 1719 earthquake, the 1754, May 1766, and August 1766 earthquakes (Ambraseys and Finkel, 1991) caused complete rupture along segments of the northern strand from Adapazarı to the Gulf of Saros, crossing the Marmara Sea as a sequence.

The 17 August 1999 İzmit earthquake is the seventh earthquake of the westward-migrating earthquakes along the North Anatolian fault since the 1939 Erzincan earthquake. The 1912 earthquake occurred between Gaziköy and the Gulf Saros, and it was as large as the 17 August event (Ambraseys and Finkel, 1987). The 1894 event, which caused considerable damage in İstanbul, occurred between Hersek delta and Çınarcık basin (Eginitis, 1895; Ambraseys and Jackson, 2000). Figure 19 shows slip distribution and location of the eighteenth- and twentieth-century earthquakes in the Marmara Sea region. This reveals that there is a seismic gap in the Marmara Sea between the Hersek delta and Gaziköy and between the 1912 and 1999 İzmit earthquakes. The last earthquakes in the Marmara Sea were in 1766 May and 1894 in the central Marmara Sea and Çınarcık basin respectively. Modeling of the 1999 İzmit earthquake illustrates that this earthquake increased the earthquake hazard on the Yalova segment and other segments in the Marmara Sea (Hubert-Ferrari *et al.,* 2000; Parsons *et al.,* 2000), which is the western continuation of the northern strand. It also increased stress on the Düzce–Bolu segment at the eastern part of the Düzce–Hendek fault, which ruptured approximately 3 months later on 12 November1999 as the *M* 7.2 Düzce earthquake (Figs. 3 and 4).

The study of the 17 August 1999 İzmit earthquake, Global Positioning System (GPS) slip rate, historical earthquake records, and the Coulomb modeling suggest that there is significant earthquake hazard in the Marmara Sea (Hubert-Ferrari *et al.,* 2000; Parsons *et al.,* 2000). According to GPS measurements, particularly the central Marmara segment of the Marmara strand should have more than 4-m-slip accumulation since the May 1766 earthquake. If we add stress increase caused by the 17 August earthquake the central Marmara segment is the one most likely to rupture in near future. Parsons *et al.* (2000) calculated that the probability of an $M > 7$ earthquake is about 62 ± 15% for the next 30 yr.

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İstanbul Technical University
Dept. of Geology
Ayazaga, İstanbul, Turkey
(A.B., H.S.A., G.S., Z.Ç., A.D., B.Y.)

Osmangazi University
Dept. of Geology
Eskisehir, Turkey
(E.A.)

Institut de Physique du Globe
Paris, France
(R.A., B.M., J.B.C.)

Southern California Earthquake Center
Los Angeles, California
(T.R., J.R.D., R.H., T.D., S.C., A.T.)

U.S. Geological Survey
Menlo Park, California
(T.F., R.L., H.S.)

William Lettis and Associates
Walnut Creek, California
(W.L., J.B.)

Pacific Gas and Electric
San Francisco, California
(W.P.)

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